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IRRIGATION BY SPRINKLING

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IRRIGATION BY SPRINKLING[1, 2, 3]

J. E. CHRISTIANSEN[4]

INTRODUCTION

THIS BULLETIN will discuss the application of irrigation water by sprinkling and will present the results of several years' research, together with general information. Although intended especially for farmers who are now operating sprinkler systems or contemplating irrigation by this method, the bulletin includes some technical material essential to an economical design of sprinkler systems—material of interest primarily to engineers, irrigation contractors, and others engaged in manufacturing, selling, and installing sprinkler equipment. The more technical aspects of the subject, and most of the experimental results, appear in the latter part of the bulletin. A closing section presents in nontechnical form a discussion on design and operation of sprinkler systems.

THE USE OF SPRINKLER SYSTEMS FOR IRRIGATING AGRICULTURAL CROPS

Sprinkling as a method of irrigation has been practiced in California and elsewhere for about forty years. Before 1920 it was limited primarily to truck crops, nurseries, and small fruits, and was practiced mainly as supplemental irrigation in the more humid regions. Stationary overhead sprinkler systems were first used in citrus orchards in some sections of California about 1920. Most of such systems were installed, however, between 1924 and 1928 in areas where surface irrigation was not entirely satisfactory because of unusually pervious soil or because of topographic features. Along the foothills east of Pasadena, the soil is gravelly in many places and the slopes are rather steep for furrow irrigation, except where orchards are laid out on contour grades; overhead sprinkling of orchards had its inception in these areas.

Many of these systems were installed because of the extravagant claims made by those interested in manufacturing or selling the equipment. Sprinkling was supposed to save large quantities of water, to control insects, frosts, and diseases, and to increase production. Some of these early attempts proved unsatisfactory because of poor equipment and

[1] Received for publication September 26, 1941.

[2] This bulletin supersedes Extension Circular 4, *Irrigation by Overhead Sprinkling*, by H. A. Wadsworth, published in 1926.

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too wide spacing of sprinklers. After trial, a few of the systems were abandoned, and furrow irrigation was resumed. As was gradually recognized, sprinkling is not a cure-all; good results can be obtained only when systems are properly designed and installed, with the right equipment. Most of these original overhead systems represented investments of $300 to $500 per acre or more. Since the drop in citrus prices about 1930, relatively few stationary sprinkler systems have been installed.

In 1932 the farm advisor's office in Los Angeles County made a survey[5] of overhead irrigation of orchards in that area. One hundred growers, representing 1,504 acres, were questioned. The majority were, apparently, well satisfied with their overhead systems. They had experienced very little trouble with the equipment and believed that the change to sprinkling had increased production. Some had had trouble with sprinklers stopping; others with packing of their soil, runoff, and the like. Only two reported abandoning the system. The survey also indicated that the use of water was practically the same as for furrow irrigation.

Lightweight steel pipe with quick-couplings for portable sprinkler systems was first used about 1930. Its introduction completely changed the picture of sprinkling as a method of irrigation. Whereas with stationary systems, the main consideration was the initial outlay, with portable systems for field crops the equipment costs sometimes as little as $10 to $15 per acre and usually under $50. The expense of operation became the important item; this, annually, sometimes exceeded the investment in equipment. These portable sprinkler systems were better adapted to, and were used more on field and truck crops than in orchards. According to a survey made in 1936, a greater acreage of sugar beets was being sprinkled than any other crop. Sprinklers were being used on nearly all field and truck crops as well as in orchards.

Most of these systems are used in areas not adapted to surface irrigation. Near Clarksburg on the Sacramento River south of Sacramento, subirrigation had been practiced almost exclusively. In 1931, probably because a series of dry winters resulted in insufficient natural leaching, alkali spots were beginning to appear in many places; they were especially noticeable in fields planted to beans. To counteract the upward movement of the soluble salts, portable sprinkler systems were tried. Within a few years more than a hundred systems were in use in the Sacramento Delta, farther north in Sutter Basin, and near Meridian. Because of the high water table in these areas, the irrigation requirement was low compared with that in other places of similar climate. Sprinkler

[5] Salter, A. G. Orchard overhead irrigation. Pacific Rural Press 131(11):346–47. Mar. 14, 1936.

systems could therefore cover relatively larger areas at lower per-acre costs. Since surface irrigation was not feasible in many places, comparisons were most frequently made between sprinkling and subirrigation; in general, results were better with sprinkling.

Sprinkling has also become very popular for irrigating certain truck crops near Moss Landing in the Salinas Valley, where both the type of soil and topography have been reasons for changing from surface methods. Another factor that makes sprinkling economical in the coastal areas is the lower water requirement due to low temperatures and high humidities.

Portable sprinkler systems have also been installed in many scattered areas for irrigating pastures and field crops. They have been used rather extensively in Oregon, especially for pasture irrigation. Many were installed in areas where previously irrigation had not been practiced.

About the same time that portable sprinkler pipe was introduced, under-tree orchard sprinkler systems also came into use. These systems consist of small sprinklers, mounted on short risers, which cover the areas between adjacent trees. Because stationary equipment of this type interferes with cultivation and with other orchard practices, most of these systems are portable. The simplest type of portable unit consists of several small sprinklers on low stands joined with ¾-inch garden hose. This portable unit is supplied from small garden hydrants on buried supply lines. Later a drag-type sprinkler system using lightweight steel tubing joined with special couplings was developed. The introduction of portable sprinkler pipe in small sizes led to the use of this pipe for under-tree orchard systems. The last few years have seen rapid advances in the development of under-tree equipment. Orchard sprinkling with such systems is practiced mainly in San Diego County, in the La Habra Heights section of Los Angeles County, and in some parts of Santa Barbara and Ventura counties.

GENERAL CHARACTERISTICS AND CLASSIFICATION OF SPRINKLER SYSTEMS

All sprinkler systems have certain features in common. They consist essentially of pipes with sprinklers or nozzles for distributing the water over the area to be irrigated. To accomplish this, the water must be discharged at a high velocity, which is obtained by operating the system under pressure. This pressure may be provided by gravity from a water source at a higher elevation or by pumping.

Irrigation by sprinkling differs from other methods in that the water is distributed over the soil by mechanical means, whereas for other methods of irrigation the water is finally distributed by the soil itself.

The uniformity of application by sprinkling depends primarily upon the ability of the system to apply equal amounts to all parts of the area. For surface irrigation the uniformity depends upon the surface condition, and upon uniform permeability of the soil as well as the ability of the system to distribute the water uniformly to local areas. Although sprinkling is frequently called an imitation of rain, it differs from rain in many respects. The distribution is never so uniform as with rain. The rate of application and amount applied are largely under control, a feature that overcomes some of the detrimental effects of rainfall. The effect on plants may be different, especially in connection with the spread of disease. Since sprinkling is commonly carried on during warm, sunny days it has little effect on the humidity except during the application, whereas rain is generally associated with cloudy weather and high humidity lasting a considerable time.

Despite certain common characteristics, sprinkler systems have many differences. They may be classified according to their portability, or according to certain mechanical features. They are called "portable" when most of the mechanical equipment can be readily moved from place to place over the area irrigated; "semiportable" when only a minor part of the equipment is moved, such as the risers and sprinkler heads; and "stationary" or "permanent" when all the equipment is fixed. Obviously, definite lines cannot always be drawn between these three groups, especially between portable and semiportable systems. This classification overlaps completely on any grouping according to mechanical features.

Sprinkling is frequently called "overhead irrigation." This is somewhat confusing because orchard systems are often classified as "overhead" or "under-tree." The overhead systems distribute the water over the tops of the trees, whereas under-tree systems distribute it near the ground between and under the overhanging branches of the trees. Under-tree sprinklers are sometimes called "low-head," or "ground" sprinklers. Either of these systems may be portable or stationary. Because stationary under-tree sprinklers interfere with cultural practices in an orchard and are also more expensive, most under-tree systems are portable. Although many overhead systems are portable, the high risers make them somewhat difficult to move. The pipe lines of stationary overhead systems are generally placed underground and the sprinklers directly over the trees, completely out of the way of other orchard operations.

Sprinkler systems may also be classified according to method of distributing the water, whether by rotating sprinklers, by fixed heads, or by nozzles along a pipe line which is rotated back and forth through an angle of about 90 degrees to cover a strip on each side of the line. This latter type is called a nozzle line.

STATIONARY SPRINKLER SYSTEMS

Stationary systems are used to a considerable extent in California. Most of the original orchard systems were of this type, with rotating sprinklers mounted on high risers over the trees. Other kinds of stationary systems include those with fixed sprinkler heads, used extensively for lawns and ornamental plantings and to a limited extent for orchards; and nozzle lines used principally for truck crops, nurseries, and other special purposes.

ROTATING SPRINKLER SYSTEMS

Rotating sprinklers have capacities of 1 to more than 100 gallons per minute. Some of the larger sprinklers are designed for pressures of 60 to 100 pounds per square inch, and will cover circles up to approximately 200 feet in diameter, whereas some of the small ones will operate on pressures of 10 pounds per square inch or less. In general, the larger the nozzles, the higher the pressure required for best performance. Some very large sprinklers, with capacities of several hundred gallons per minute, have been used for irrigating bananas in Central and South America, and for other crops in certain European countries. Because of the extremely high pressures required for their operation, these large sprinklers are not considered economical in California. For supplemental irrigation, where the annual water requirement is low, high pressures and large sprinklers may be more economical than small sprinklers because of the greater permissible spacing of pipe lines.

Rotating sprinklers are of two types: whirling sprinklers, that rotate rapidly, and slow-revolving sprinklers, that rotate slowly. Slow-revolving sprinklers ordinarily rotate at a speed of one or two revolutions per minute; some much slower. The slower a sprinkler rotates, the larger the area it will cover. When operating under pressures of about 40 pounds per square inch, slow-revolving sprinklers will cover areas up to about 120 feet in diameter. Whirling sprinklers of similar capacities, operating under equal pressures, will cover areas 50 to 70 feet in diameter. The slow-revolving sprinklers are therefore more desirable, since they permit a greater spacing of pipe lines.

Slow rotation minimizes wear, and thereby prolongs the life of the sprinkler. Various types of driving mechanisms are used to produce a slow rotation and prevent the sprinklers from stopping. Sometimes slow-revolving sprinklers vary greatly in their speed and this variation may appreciably affect the distribution of water. Whirling sprinklers tend to rotate at a more constant rate because of the momentum of the revolving parts. They are generally less expensive than slow-revolving

sprinklers. Figure 1 shows a few of the different types of rotating sprinklers.

Arrangement and Spacing of Sprinklers.—Though absolute uniformity is not essential, large variations in depth of application are not desirable, particularly with stationary systems where the cumulative effect of either excessive or inadequate amounts becomes serious. The distribution of water from sprinklers depends upon several factors. Careful study, however, indicates that approximately uniform application is possible with sprinklers covering circular areas. The application can be uniform only when (1) the type of pattern produced is correct for the arrangement of sprinklers, (2) the sprinklers are correctly spaced, (3) the sprinklers rotate at a uniform rate, and (4) there is no appreciable wind.

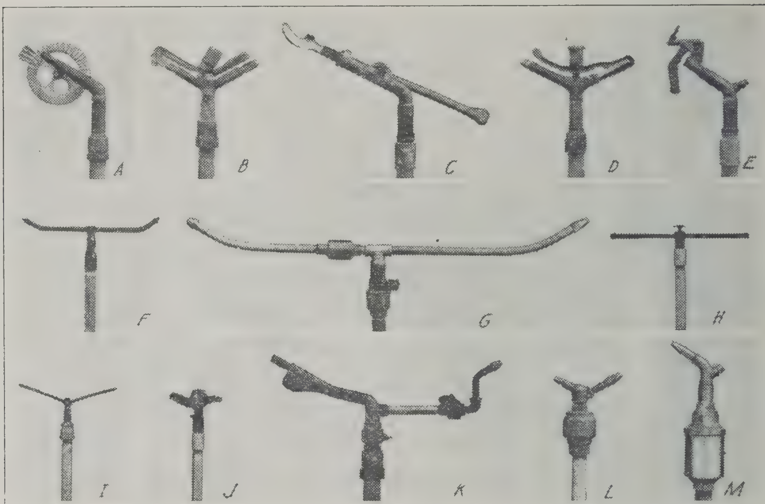

Fig. 1.—Different types of rotating sprinklers. Types with external driving mechanisms: *A*, spinning wheel type; *B*, *D*, and *J*, oscillating spring types; *C* and *E*, pendulum types. Reaction-drive sprinklers: *F*, *H*, and *I*, whirling sprinklers; *G* and *K* have vibrators for slow rotation. Internal-drive sprinklers: *L*, friction-drive type, and *M*, gear-drive type.

For stationary installations, sprinklers are arranged in squares, triangles, or rectangles with a greater spacing between the pipe lines than between sprinklers on the line. For stationary orchard systems, the sprinklers are usually mounted over certain trees. With trees planted on a square, an equilateral-triangle arrangement of sprinklers is not practicable. All sprinkler spacings must be multiples of tree spacings, which generally vary from 18 to 24 feet. The maximum practical spacing for medium-sized slow-revolving sprinklers operating under adequate pres-

sure is a sprinkler every fourth tree, in every fourth row. For this spacing, a triangular or staggered arrangement will probably give better distribution than a square. For most sprinklers, a spacing of three tree rows in both directions would be better, in which case staggering is not

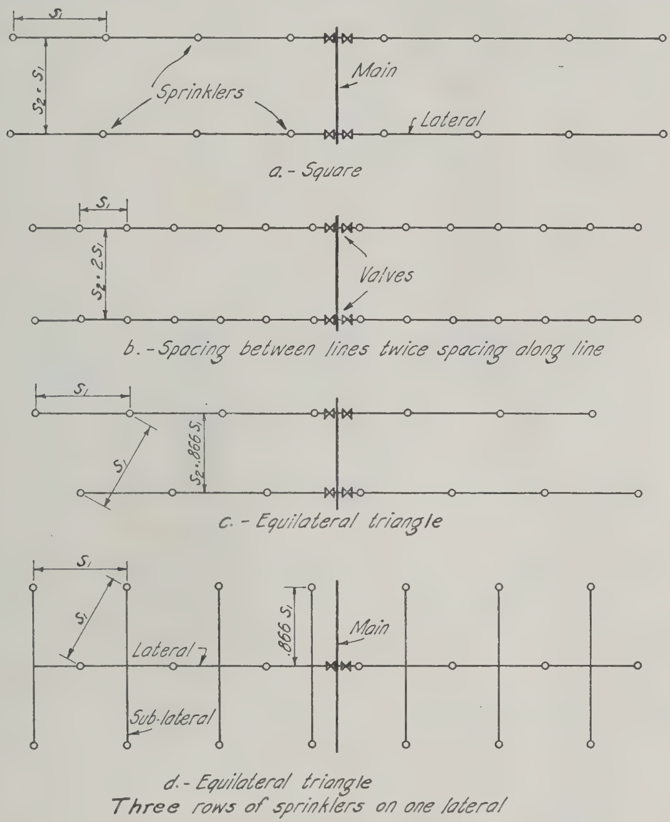

Fig. 2.—Some of the various arrangements of sprinklers and pipe lines for sprinkler systems. The letters S_1 and S_2 denote spacing between sprinklers, and spacing between pipe lines, respectively.

practicable. Other possibilities include a sprinkler in every other tree in every third or every fourth row with the sprinklers staggered, or arranged in a rectangle. According to analyses of both actual and geometrical patterns (discussed in a later section) with fairly close spacings along the line there is little to be gained from staggering. Square and rectangular arrangements of sprinklers generally permit better distribution around the borders of the field than triangular or staggered arrangements.

Layout of Pipe Lines.—The usual arrangement of pipe lines for stationary sprinkler systems consists of a central main with parallel laterals at right angles to the main line, carrying the sprinklers. Each lateral is provided with a shutoff valve so that it can be operated independently. Since stationary systems are generally confined to relatively small areas such as 10-acre tracts, these laterals will seldom carry more than six or eight sprinklers. Larger areas are sometimes divided into smaller sections treated separately. In all cases a main supply line through the center of the area is most desirable. Where the water comes from a well, the cheapest arrangement is to place the well approximately in the center of the tract to be irrigated; this minimizes the pipe sizes required. Figure 2 shows various arrangements of sprinklers and pipe lines.

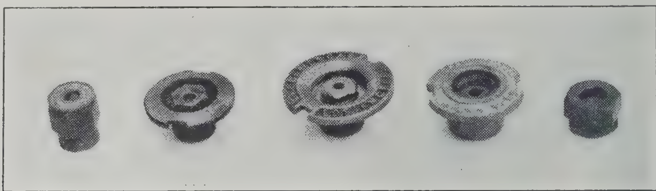

Fig. 3.—Different types of fixed heads. The center three are lawn heads and the two end ones are commonly called shrubbery heads. Both are used for under-tree orchard systems.

For an equilateral-triangle arrangement of sprinklers, about 9 per cent in length of pipe required will be saved if three rows of sprinklers are supplied from one lateral (arrangement *d* compared with *c*, fig. 2). A similar arrangement can be used for sprinklers placed in a square. Although, in this case, there is no saving in total length of pipe required, and the main laterals have to be increased in size to carry three times as much water, the cost may be less, since the sublaterals can be smaller. For example, a 3-inch main lateral with 1-inch sublaterals might replace three 2-inch lines.

SYSTEMS WITH FIXED SPRINKLER HEADS

Fixed heads are used mainly for lawns and for portable under-tree systems for orchards. These heads have no moving parts; they cover areas 15 to 25 feet in diameter with a fine spray fairly evenly distributed. Although most fixed heads cover circular areas, some are designed to cover square areas. Figure 3 shows a few fixed heads of different types.

The use of fixed heads on field and orchard systems is limited. For stationary systems, the cost is excessive, because of the close spacing required, and furthermore, the closely spaced heads are objectionable from the standpoint of cultivation. The minimum rate at which water

can be applied with these sprinklers is often too high; the soil cannot absorb it rapidly enough to prevent accumulation of water in low places or runoff. Normal rates of application with these heads range from about 0.7 inch to 3 inches per hour, whereas with rotating sprinklers rates as low as 0.1 inch per hour are possible, and rates of 0.2 to 0.5 inch per hour are usual. Many bare soils do not absorb water rapidly enough to permit the use of fixed heads, except when only light applications are made.

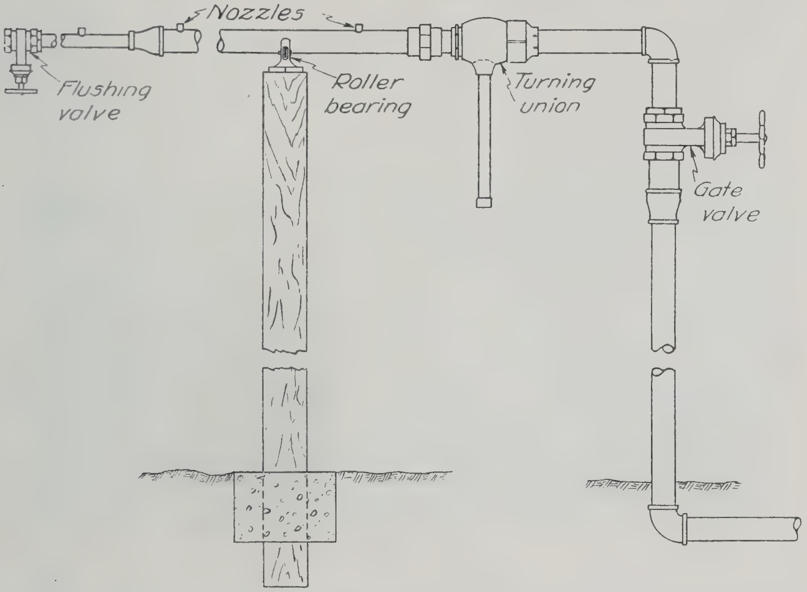

Fig. 4.—Detail of typical nozzle line assembly for hand rotation. The special fittings required can be secured from dealers handling sprinkler equipment. (From Ext. Cir. 4.)

On the other hand, simplicity, absence of moving parts, and low cost make fixed sprinkler heads highly desirable where conditions permit their use, such as for portable under-tree orchard systems on permeable soils.

NOZZLE LINES

Nozzle lines consist essentially of parallel lines of pipe (¾ to 1½ inches in size) equipped with small brass nozzles, usually spaced 2 to 4 feet apart (fig. 4). Being relatively expensive, they are generally used only for crops yielding a high gross return, such as certain truck crops and small fruits, and for nurseries, greenhouses, lawns, and other special purposes. They are occasionally used in orchards, especially on terraced plantings.

The pipe is generally supported 4 to 7 feet above the ground on posts spaced about 15 feet apart. Where it is not necessary to provide passage underneath for cross-cultivation, lines about 4 feet above the ground permit convenient access to the nozzles for servicing. Occasionally nozzle lines are supported by a suspension cable from much higher poles 100 to 200 feet apart, an arrangement that lessens the obstruction to cultivation. To cover a strip of ground on both sides of the lines they are oscillated through an angle of about 90 degrees, generally by means of a water-operated oscillating motor. Figure 5 illustrates this type of system.

Fig. 5.—Nozzle line used for irrigating strawberries. This line is rotated back and forth by a hydraulic oscillating motor at the head end of the line. (Six nozzles, of a special type, shown in the foreground, were being tested for distribution of water; this accounts for the difference in appearance of the jets.)

A complete line of equipment is available for nozzle lines, including a variety of nozzles, ranging from those that throw a round jet for maximum coverage, to others that have deflectors to break up the jet for narrower strips. Some nozzles, having orifices of triangular shape, are designed to distribute the water over a considerable area without oscillating the line. Special roller saddles on top of the posts carry the pipe and reduce to a minimum the friction in rotating the line. These fittings are available for either wood or pipe posts. Special hand-turning unions are also available. For best performance, however, nozzle lines should be equipped with oscillators that slowly rotate the line, resulting in a fairly uniform distribution of water when the lines are correctly spaced. These oscillators are usually double-acting piston devices that operate

from the water pressure. Being fairly expensive, they are sometimes moved from one line to another, one oscillator being used for several lines. Sometimes one hydraulic oscillator is used to rotate a number of parallel lines by means of cables attached to arms on each line. For good results the mechanics of such systems must be carefully worked out.

Because of the very small diameter of the nozzles used on these lines they are easily clogged, especially when the water is from an open source where algae might grow. Special screens are available for such conditions. One make of equipment utilizes small individual screens on the nozzles; but since these project into the pipe and increase the frictional resistance, they are less desirable than properly designed screens at the head of the line. Screens should have ample area in order to cause only a small resistance to flow even when much of the total area is clogged. They must also be designed to facilitate cleaning. If the source of water is free from anything that would cause clogging, screens are unnecessary. Flushing valves are used at the end of the line for flushing dirt and pipe scale from the line. Such material always tends to settle out and to clog nozzles only near the end of the line.

Special union couplings with squared sockets are available to facilitate the lining up of the nozzles. They are especially important on portable lines that are moved from one set of supporting posts to another.

Since the discharge of all nozzles varies with the pressure, the only way to secure a uniform discharge along the line is to limit the pressure loss to a small part of the normal pressure on the line. Frequently the friction loss is appreciable; the pressure along most of the line may be very different from that at the head. Pressure-gauge connections with shutoff cocks at each end of the line are desirable, for they permit the pressures to be readily determined by means of a portable pressure gauge. A permanently mounted pressure gauge is sometimes used at the head end, but seldom are the pressures determined at other points. Friction loss in pipe lines is discussed in detail later.

Nozzle lines are usually operated at pressures of 25 to 40 pounds per square inch. The width of strip effectively covered increases with increase in pressure up to about 40 pounds per square inch. Above this there is little or no increase in width because of a greater dispersion of the jets. Where the pressure is adequate, the lines are spaced about 50 feet apart. Sufficient pressure should be provided to overcome friction losses and to leave sufficient pressure for effective operation.

Nozzles of the type commonly used on nozzle lines have capacities ranging from about 0.15 to 0.30 gallon per minute at a pressure of 30 pounds per square inch. Special nozzles, occasionally used, have capacities up to 0.70 gallon per minute. Friction loss in nozzle lines, being at

any point proportional to the square of the velocity, will vary appreciably with different combinations of nozzles and pipe sizes, and this must be kept in mind when designing sprinkler systems.

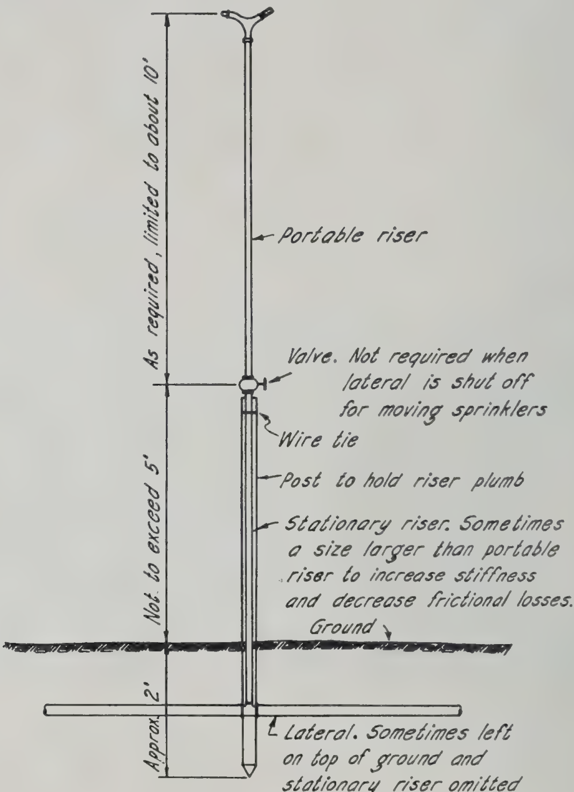

Fig. 6.—Details of riser for semiportable sprinkler system using portable sprinklers on a stationary pipe distribution system.

SEMIPORTABLE SPRINKLER SYSTEMS

Some sprinkler systems have stationary pipe lines and portable sprinklers that are moved from place to place. They are especially desirable in orchards; they are less expensive than stationary systems and they obviate certain practical difficulties encountered with portable systems, such as holding high risers in vertical positions and in moving them from place to place. Figure 6 illustrates a common arrangement. A short stationary riser with valve extends 4 or 5 feet above the ground. The upper part of the riser and sprinkler is portable, and only the number

operated at one time are required; thus a considerable saving in the cost of sprinklers is effected. For example, 6 or 8 sprinklers may suffice for a 10-acre tract, whereas a stationary system would require more than 100. In addition, there is an appreciable saving in the cost of pipe lines because smaller sizes may be used when each sprinkler is operated on a different lateral. For example 1¼-inch laterals may suffice, whereas 2-inch (or larger) laterals may be required where several sprinklers are operated simultaneously on one lateral.

A somewhat similar type of semiportable system is extensively used for parks, golf courses, athletic fields, and other large lawns. A stationary-pipe distribution system is installed with an automatic shutoff valve at each sprinkler location. Sprinklers are attached to these valves by simply inserting a special coupler and giving it a turn. These valves are sold under such trade names as "super valves," "snap valves," and "lawn valves." Such systems are also suitable for certain agricultural crops, though the cost of the automatic valves makes them rather expensive.

When overhead sprinkling first came into use, a popular type of semiportable system utilized sprinklers mounted on a high riser on a portable stand and attached to a hydrant with garden hose. This arrangement permitted relatively wide spacing of laterals and hydrants, since several sprinkler locations could be served by one hydrant. The locations of the sprinklers can be varied for different irrigations to effect a more uniform seasonal application for all places in the orchard. The arrangement is not, however, entirely satisfactory because of the difficulty of moving the sprinklers.

Another type of system used in orchards that might be classed as semiportable consists of stationary pipe lines supplying water to portable under-tree sprinklers. These are discussed more fully in the section on "Under-Tree Sprinkler Systems for Orchards."

PORTABLE SPRINKLER SYSTEMS

The type generally known as a portable sprinkler system originated about 1930. Essentially it consists of a sprinkler line of special lightweight portable pipe with quick-couplings, together with a pumping plant. Sprinkler pipe comes in standard lengths of 20 feet; other lengths are furnished on special order. Sprinklers are usually spaced 20, 30, or 40 feet apart. The pipe is moved across the field by carrying one length at a time. Several makes of systems are available, each with a different kind of coupling, some of which are shown in figure 7. These systems are used largely for irrigating field and truck crops, such as sugar beets, peas, beans, and onions.

Many systems operate with a portable pumping plant supplied from a field ditch along one side or through the center of the field. The entire system can be moved from one field to another. Where the water supply is obtained from wells or where, because of the topography, ditches through the field are not feasible, a stationary pumping plant and pressure supply line are used.

PORTABLE SPRINKLER TYPE

When these systems first came into use only 4-inch pipe was available. Now some of the makes can be obtained in sizes of 1½, 2, 3, 4, 5, and

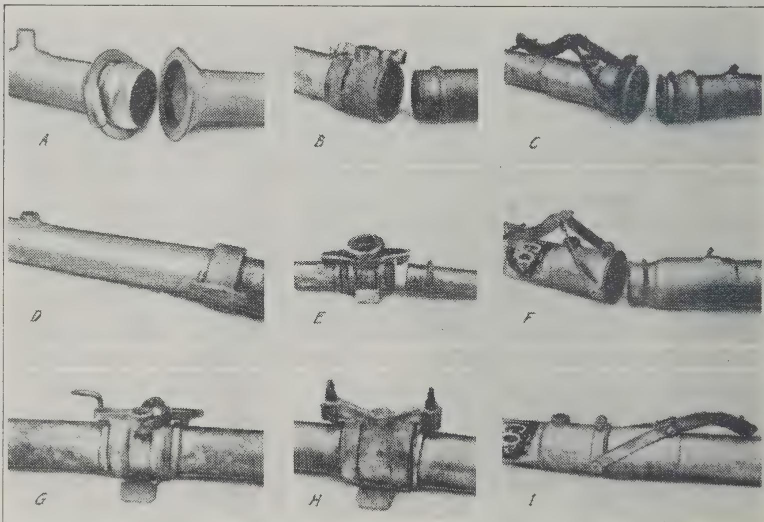

Fig. 7.—Some of the different types of portable sprinkler-pipe couplings: *A*, Shur-Rane, ball-and-socket type; *B*, Montague; *C*, Calco (3-inch); *D*, Rain Storm; *E*, Pierce; *F*, Calco (4-inch); *G*, Wilson; *H*, Shur-Rane; *I*, Calco (4-inch, coupled).

6 inches and in any desired length. For field-crop systems, lengths of 30 and 40 feet are sometimes used. For orchard systems, pipe of the same length as the tree spacing is desirable. The longer lengths are slightly cheaper because they require fewer couplings.

Most of the portable sprinkler pipe is made from electric-welded steel tubing, 16-gauge being used for 4-inch and larger pipe, and 18-gauge for 3-inch and smaller sizes. Lighter-weight sprinkler pipe, made from 22- and 24-gauge metal, has come into use recently. This is somewhat lighter to handle and is strong enough to withstand the pressure required; but it is less durable than the heavier pipe. Some of the couplings (fig. 7) are attached permanently to the pipe, whereas others are separate

and simply connect two lengths. In some, the sprinkler outlets are in the couplings; in others, the outlet is welded to the pipe a short distance from the coupling. The pipe is usually galvanized after fabrication.

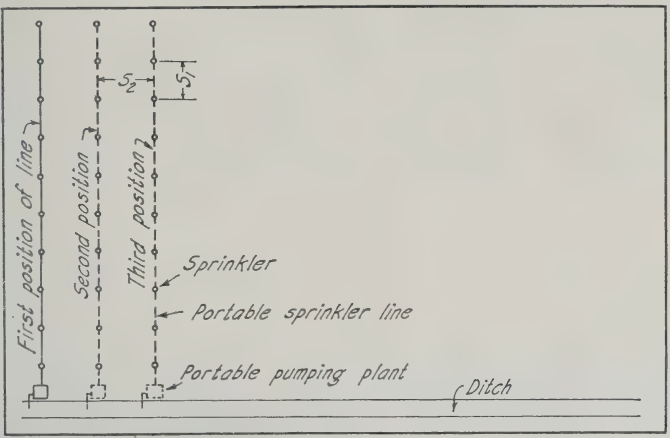

Fig. 8.—Single-line arrangement of portable sprinkler system supplied from a ditch along one side of the field.

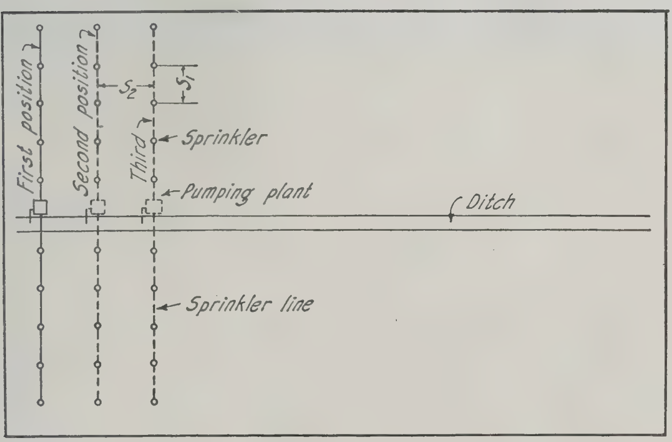

Fig. 9.—Split-line arrangement of portable sprinkler system supplied from a ditch running through the center of the field. This results in a more economical operation than with the single-line arrangement shown in figure 8.

ARRANGEMENT OF PORTABLE SPRINKLER LINES AND METHODS OF OPERATION

Use of Field Ditches.—There are several possible arrangements of portable sprinkler lines. The most common are the single-line and split-line arrangements (figs. 8 and 9). The term "split line" is a misnomer,

but has become more or less established by usage. With the single line the supply ditch is located along one side of the field, and the line of portable pipe extends across the field. This arrangement is practical for pipe lines not exceeding 1,000 feet in length. It is generally used where an existing ditch, from which the water can be pumped, is located along the field border. An example appears in figure 10. The sprinklers are operated until the desired application is made; then the pumping plant is shut down while the pipe and pumping plant are moved to the next position. The pipe is usually moved by two men carrying one length at a time. Under ordinary conditions, pipe can be moved at an average

Fig. 10.—Portable sprinkler system irrigating beans in Sutter Basin; a single line of 4-inch pipe with sprinklers 20 feet apart. The portable pumping plant is at the far end of the line.

rate of about 30 lineal feet of pipe per minute. From 5 to 10 minutes are required to move the pumping plant and start operation. Where only light applications are needed and lines are operated in each position for a relatively short period—two hours or less—a large part of the total time is lost in moving. Another disadvantage of the single-line arrangement is the high friction loss which is about eight times as great as with split lines of the same size and total length and same capacity. Single lines often necessitate the use of larger pipe, or smaller sprinklers, than split lines.

The split-line arrangement is the most satisfactory for portable sprinkler systems using portable pumping plants. It permits the use of minimum pipe sizes and allows for nearly continuous operation of the pumping plant. The pipe line on one side of the pump is shut down and moved to the next position while the line on the other side continues to operate. The pump is then shut down, moved to the next position, connected to the line that has been moved, and started up. The other line is then moved, connected to the pump, and turned on. With the same

throttle setting, and with only one of the two lines in operation, the pressure is increased by about 50 per cent, and the discharge through the one line is about 60 per cent of the two lines. The plant is therefore in effective operation most of the time. The actual time lost by moving is slightly less than the time required to move one of the lines. The operating efficiency is therefore considerably higher than for the single-line arrangement; when feasible, the split-line arrangement should be used.

Sometimes two parallel lines are operated on the same side of the supply ditch as shown in figure 11. When it is time to move, the front

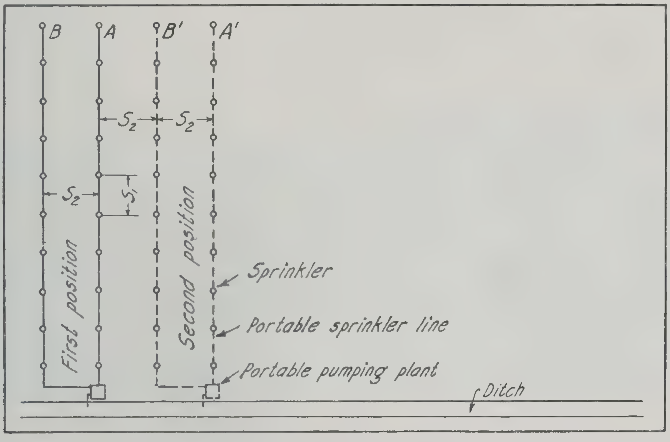

Fig. 11.—Double-line arrangement of sprinklers illustrating how two parallel sprinkler lines can be operated on the same side of the supply ditch. This arrangement being undesirable should be used only where other arrangements are not feasible.

line, *A,* is shut down and moved twice the spacing of the lines to *A′*. The pumping plant is then brought up, and this line is placed in operation. The rear line, *B,* is then moved to *B′*, and put in use. This method provides for nearly continuous operation of the pumping plant but is objectionable because it necessitates carrying all the pipe twice as far and moving the rear line across wet ground. It should be used only where other arrangements are not practicable. Figure 12 shows a sprinkler system using a double line.

Another method of operating, called the alternate-line arrangement, is used where the pumping-plant capacity is not adequate for operating two lines at a time. The arrangement of the portable lines is usually the same as for the split-line arrangement. The method is similar except that only one line is operated at a time. After the second line is moved, the water is not turned on until time to turn off the first line. This arrange-

ment permits almost continuous operation of the pumping plant at full capacity, but requires twice as much pipe as a single line. Because of the higher operating efficiency, a larger area can be served by a pumping plant of a given capacity. This method is especially suitable where the pipe is moved at frequent intervals.

Use of Pressure Supply Line.—Where water is supplied under pressure, or where for other purposes a stationary pumping plant is more desirable, water can be supplied to the portable sprinkler lines through a pressure supply line. The ideal arrangement is shown in figure 13 illustrating a supply from a well located in the center of the field. With

Fig. 12.—Double-line 3-inch portable sprinkler pipe with sprinklers spaced 40 feet apart, being used to establish Ladino clover pasture.

the pumping plant at this position, minimum pipe sizes can be used, and friction losses are less than where pumping plants are located at the boundaries of the field. The water is supplied to the portable lines from hydrants located along the pressure line. This arrangement, although the most satisfactory from the standpoint of operation, is somewhat more expensive than systems using portable pumping plants, since a stationary pressure supply line represents an investment of $25 to $50 per acre—usually more than the cost of the portable pipe. Any number of portable laterals can be used on one pressure supply line. With two or more laterals the pumping plant can be operated continuously. When several laterals are used, they should be arranged so that the friction loss in the supply line will be a minimum, and so that the laterals will not interfere with each other. A large installation of this kind, with several laterals, is used in the San Joaquin Valley for irrigating cotton. A crew is kept busy moving pipe. This provides more effective use of the labor and may therefore result in an appreciable saving.

Under some conditions a portable pressure supply line is more feasible than a stationary one. This is especially true where a large sprinkler system is used to irrigate several fields and the portable line can be used effectively in several locations.

Portable pressure mains are usually not provided with valve outlets, but are directly connected to the laterals. The main line is shortened or extended by removing or adding sections of pipe to fit the various locations of the laterals. When two or more laterals are supplied from one main, portable valves are required, or the system must be shut down

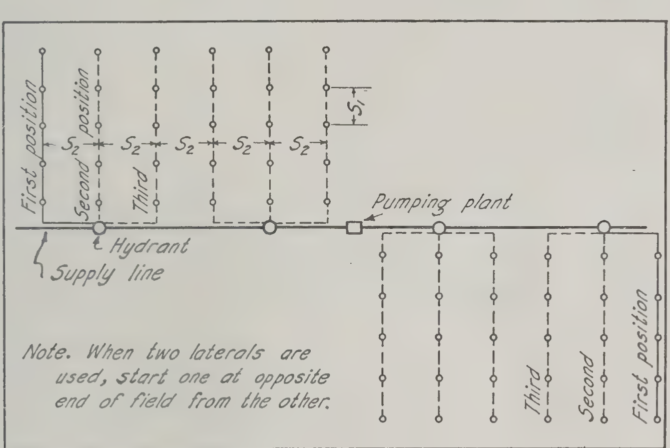

Fig. 13.—Arrangement of a portable sprinkler system operating from a pressure supply line with a stationary pumping plant supplied from a well.

while both laterals are moved. Although portable supply lines may offer a saving in pipe cost, they are less convenient than stationary supply lines.

Drag-Type Sprinkler Systems.—Since the main cost of operation of portable sprinkler systems is for labor for moving portable sprinkler pipe, some interest has been shown in drag-type systems, especially for orchards, in which the portable pipe is moved by dragging endwise. The power for moving the pipe may be supplied by a small tractor, a team, or one horse. Small units are sometimes moved by hand. When one or two lengths of pipe are used ahead of the first sprinkler on the line, it is not necessary to work on wet ground to move the pipe.

Figure 14 illustrates a completely portable drag-type system with a portable pumping plant supplied from a ditch through the center of the field. With such systems the portable lateral is taken apart and moved forward with the drag unit. A wheel cart at the head end of the unit is

used both for holding the risers in a vertical position and for carrying the lateral forward. A more satisfactory arrangement of the drag-type system (fig. 15) illustrates the use of a stationary pressure main and laterals with portable drag units. Relatively small pipe can be used for the laterals when the drag units are distributed so that only one or two are served by each lateral. Drag-type systems for orchards are further discussed later.

SPRINKLERS FOR PORTABLE SYSTEMS

Slow-revolving sprinklers are most satisfactory for portable systems. Because of continuous operation, sprinklers on portable systems receive

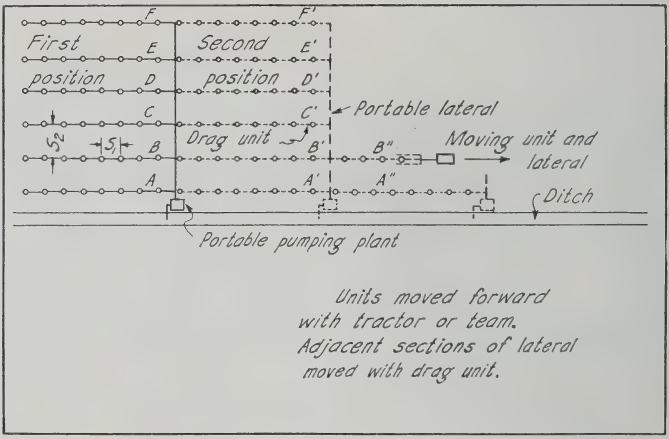

Fig. 14.—Arrangement of a drag-type sprinkler system with a portable pumping plant supplied from a ditch.

much harder service than those on stationary systems. Being subjected to considerable abuse in moving operations they must, to be satisfactory, be ruggedly built. When the portable systems first came into use, very few of the sprinklers previously used on stationary systems proved suitable. Some wore out in less than a season. On some portable systems, sprinklers may operate 2,000 hours or more during a single season, whereas on stationary systems they seldom operate more than 100 hours a season.

The length of portable line required is usually determined by the dimensions of the field, or fields, to be sprinkled; the number of sprinklers used, by the length of line and the sprinkler spacing. The capacity of the pumping plant is limited by the source of power available. In many cases, farm tractors, used primarily for other operations, are utilized. Capacities of sprinklers range from approximately 5 to 25 gallons per

minute, the choice depending upon a number of conditions. The capacity of some sprinklers can readily be changed by varying the size of nozzles. Sprinklers of the capacity that properly adapts the size of the pumping plant to the length of line required should therefore be selected. When the nozzles are too large, operating pressures are inadequate for proper performance; when they are too small, inefficient use is made of the pumping unit. Efficiency necessitates operating the sprinklers at the lowest pressure that gives satisfactory distribution of water, and using the pumping plant to full capacity.

The sprinklers are mounted on short risers directly over the portable

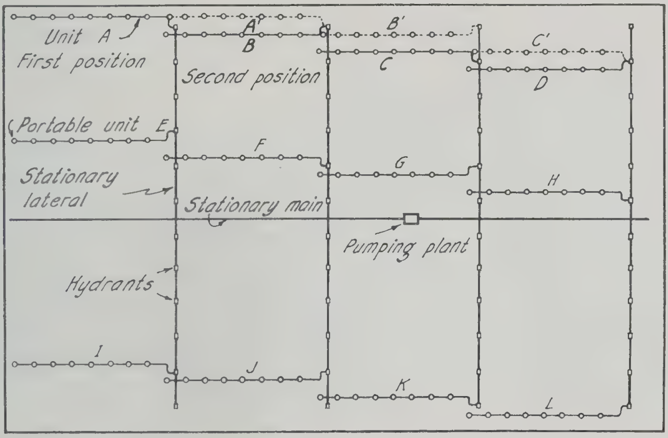

Fig. 15.—Arrangement of a drag-type sprinkler system with portable drag units supplied from a stationary pipe system. Solid lines indicate initial position of portable units; dotted lines, the position after first move. Units *E* to *L*, shown in initial position, are moved in similar manner.

pipe. These risers should be high enough to place the sprinkler over the top of the crop grown so that nothing interferes with the rotation of the sprinklers. For low-growing field crops such as sugar beets and peas, 12- or 18-inch risers are adequate; for higher-growing crops such as cotton, 30- or 36-inch risers may be necessary. High risers are objectionable because they tend to tip over; they also make it more difficult to move the pipe. In some cases, short bases are clamped to the pipe to prevent tipping. Some of the special couplings have footings to which strips of wood can be attached when required.

PORTABLE PUMPING PLANTS

There are two types of portable pumping plants: the tractor type that utilizes its own power both to operate the pump and to move from one

location to another; and the independent engine type, where a separate engine is used for operating the pump. The latter may consist of a truck, a trailer, or skids on which the pump and engine are mounted. The tractor type is most common, probably because in many instances a tractor required for other farm work is available during the irrigation season. Figure 16 shows a typical plant. Tractors eliminate the necessity of other power for moving the pump from one position to another. Because trucks tend to mire into mud along ditches, they are sometimes objectionable. Crawler-type tractors seldom become stalled in the mud.

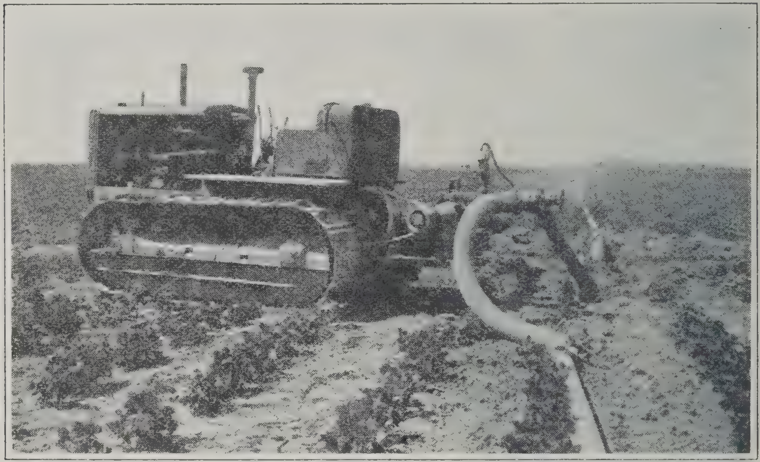

Fig. 16.—Portable pumping plant operating two ¼-mile lines of 4-inch and 5-inch pipe with 61 sprinklers; capacity, about 1,100 gallons per minute. (From Ext. Cir. 95.)

Pumps and Accessories.—Special lightweight centrifugal pumps have been designed for use on portable systems. Although not heavy, they are of rugged construction and are provided with an extra heavy shaft and bearings that will withstand operation of the pump in any position. Several sizes are available with capacities ranging from 200 to 1,200 gallons per minute, at heads of 80 to 200 feet. Detailed information concerning the performance of these pumps can be secured from the manufacturers or from dealers handling sprinkling equipment.

Sprinkler pumps are usually mounted on the front or rear end of the tractor, being supported by a special bracket welded or bolted to the tractor frame. For accessibility, they should be as low as possible.

The pump may be driven by belts, chain, or gear. V-belts are better adapted than flat belts because of the short distance between pulleys. They should be properly selected to adequately handle the load at the required speed. Manufacturers of V-belts publish complete tables giving

types and sizes to be used. Belts and chains should be protected against the weather as well as water from the sprinklers. Where separate engines are used, they are often directly connected to the pump with a flexible connection.

The pump is equipped with a noncollapsible hose of adequate diameter and length. These are available in two types, rough and smooth bore; the smooth type, which minimizes friction loss, is more desirable. Suction hose should be of the same size as, or one size larger than, the connection on the suction side of the pump, in accordance with the pump manufacturers' recommendations. The inlet end of a hose should be provided with a screen, or strainer, to prevent debris from being drawn into the pump. These strainers should have adequate openings which, even when partially clogged, will not create an appreciable loss of head. Screens of inadequate capacity may appreciably lower the pressure (increase the vacuum) on the suction side of the pump and thereby decrease the efficiency. To prevent sucking mud from the bottom of the ditch, the strainer is usually designed with openings only on the top and rear end. These strainers are generally fabricated by the manufacturer supplying sprinkler pipe, or by the dealers handling this equipment. Many portable plants have a derrick for raising and handling the heavy suction hose and strainer when moving.

When sprinkler systems are to be used to distribute fertilizer or spray solution, a 1-inch pipe connection between the suction hose and the pump case should be provided to permit the introduction of the solution into the system. Before using a sprinkler system for this purpose, one should consider the corrosive effect of the solution on the pump and sprinkler equipment. Ordinarily this is not serious if one takes the precaution of thoroughly flushing the equipment before allowing to stand after use.

The pump discharge is equipped with a valve, which must be closed to prime the pump. Where two lines are to be operated from the same pumping plant, a Y- or T-fitting and two valves are required. This permits one line to be operated at a time. Flexible discharge hoses connect the pump and the sprinkler lines.

These hoses should be long enough (10 to 15 feet) to allow the ends of the pipe to rest on the ground and to provide flexibility for making the angles or turns in the lines. They should be provided with quick-couplings of the type used on the sprinkler pipe.

Centrifugal pumps must be provided with some means of priming. For this purpose, hand-operated suction pumps are often used. Sometimes an automatic priming device is connected to the intake manifold, but it must be so arranged that the water is not drawn into the engine when the pump is primed.

Field Ditches.—Field ditches for supplying water to portable sprinkler systems must be fairly deep to submerge adequately the strainer on the suction hose. In some places where sprinkling is extensive and the water of suitable quality, ditches constructed primarily as drains are used almost exclusively for this purpose. They are very convenient since they usually require no portable dams or tappoons to hold back the flow for the pump. The large ditches are usually constructed with a drag line or a trenching machine.

Ditches constructed solely to serve a sprinkler system are usually built with a ditcher having double-wing blades mounted on a subsoiler frame. Large tractors, of at least 30 horsepower, are required to draw these ditchers. Sometimes several trips through a ditch must be made to bring it to adequate size, especially in level areas where velocities are very low. Where the ditches are constructed on any appreciable grade, portable tappoons of metal or canvas will hold back the flow and submerge the strainer. Usually they are constructed with a weir notch or opening of some type so that any excess flow will pass over without overtopping the banks of the ditch. Occasionally seepage softens the banks of the ditch, and the pumping plant becomes mired in the mud, especially where pumps are mounted on trailers or trucks. In some places the sprinkler system must always work down the ditch, with dams spaced at frequent intervals so that the pumping plant is always adjacent to a ditch that has had water in it for only a short time.

Where sprinkler systems are used on fields of irregular topography, a strip of ground along the line of the ditch may have to be graded before the ditch is constructed. This grading can be done cheaply in comparison with the cost of leveling the whole field for surface irrigation. Since ditches must be constructed in rather definite locations to serve a sprinkler system, they are not always practicable. Where the slopes are too steep, or where adverse grades are encountered, the best solution is a pressure supply line.

SYSTEMS USING STATIONARY PUMPS AND PRESSURE SUPPLY LINES

Stationary Pumping Plants.—Stationary pumping plants are employed in connection with pressure supply lines. Where water is pumped from a well with a deep-well turbine pump, the additional pressure required for sprinkling can be provided by additional stages (bowls) on the pump. This arrangement, which eliminates the necessity of a booster pump, is generally the most desirable. For an existing well with a pump designed to lift the water only to the ground surface an auxiliary booster pump may be more economical than changing over the turbine pump for

the higher heads required. A horizontal centrifugal pump of the same type used on portable systems may serve the purpose. When connected directly to the discharge pipe of the turbine pump, it requires no priming. The booster pump should have approximately the same capacity as the turbine pump so that both will be reasonably efficient when operating in series.

Stationary pumping plants are often electric-driven. Though the operating cost may be somewhat higher than for internal-combustion engines, the electric plant requires less attention—sometimes an important consideration.

One disadvantage of electric-driven plants is the difficulty of changing the speed of the pump to accommodate the sprinkler system under varying conditions, since electric-driven pumps are usually directly connected and operate at a constant speed. With engine-driven pumps the speed can be varied to produce the desired pressure at the sprinklers when the length of supply line or the number of sprinklers varies. The sprinkler system must be of such capacity and so arranged that adequate pressures can be maintained under all operating conditions. Belt-connected electric-driven pumps are sometimes advisable so that pulley sizes can be changed to provide a change in speed, especially where large fluctuations in the ground-water level are experienced during a season, or where the number of sprinklers that can be used at one time varies because of the irregular shape of the field.

Pressure Supply Lines.—As previously mentioned, pressure supply lines may be either portable or stationary. The former usually consists of extra lengths of portable sprinkler pipe without sprinklers, ordinarily of larger size. They should be large enough to carry the flow of the sprinkler system without excessive friction loss. The approximate sizes required are as follows: for flows of 50 to 100 gallons per minute, 3-inch pipe; 100 to 200 gallons per minute, 4-inch pipe; 200 to 350 gallons per minute, 5-inch pipe, and 350 to 600 gallons per minute, 6-inch pipe. Most systems using 4-inch portable laterals will require 6-inch portable supply lines. For systems with capacities of more than 600 gallons per minute, portable supply lines are not satisfactory. Friction losses in pipe lines are further discussed in a later section.

Several different kinds of pipe may be used for stationary supply lines. Welded steel lines, which are most extensively used, are less expensive than any other kind of new pipe. Other pipes suitable for this purpose include casing, standard pipe, cast iron, cement-asbestos, reinforced concrete, and reconditioned pipe and casing. Some of these materials, being rather expensive, are seldom used for agricultural sprinkler systems.

Stationary supply lines are sometimes laid on top of the ground, sometimes buried. When laid on the surface they must have expansion joints, such as long-sleeve Dayton couplings, at certain intervals to take care of the expansion and contraction caused by temperature changes. In some corrosive soils steel pipe will last much longer if supported above the ground on short piers than if laid directly on the ground or buried. Such piers must be spaced close enough together so that the pipe will not fail by bending, or crushing at the supports. Manufacturers can usually supply specific information regarding safe plans for any particular kind of pipe. Surface pipe lines generally interfere with other cultural operations, and are therefore objectionable.

Welded steel pipe is available in many sizes and weights. It is used more extensively in sizes above 4-inch diameter. Ordinarily it is supplied in 40-foot lengths and is connected together in the field by welding, special couplings, slip joints, or flanges. Welded joints are the most commonly used. One main disadvantage of welding is that it destroys the protective coating on the inside of the pipe at the joint. Sometimes an outlet is welded on the pipe at the joint so that the inside of the pipe can be recoated after welding. These outlets are then plugged. There are two methods of field welding—electric-arc and acetylene. Electric-arc welding being faster, is becoming more popular. Expansion joints are usually spaced about 500 feet apart along the line, and at summits, or near structures or branches along the line. Many kinds of fittings are available for welded pipe.

Dayton or Dresser couplings are sometimes used for connecting welded pipe. Although somewhat more expensive, they are especially desirable for galvanized pipe (where welding would destroy the galvanizing), and for small sizes, and short lines where it is not economical to provide welding equipment. They also provide for the necessary expansion and contraction along the line. They are readily installed in the field by common labor without special tools. Other types of special couplings are available.

Slip joints are frequently used for connecting welded pipe, especially where operating heads are fairly low. As they also eliminate the problem of recoating the inside of the pipe after the joint has been made, they are sometimes preferred to welding. Slip-joint pipe is provided with bell and spigot ends. The bell end of the pipe is heated to expand it and to soften the pipe coating, and the joint is made by either driving or jacking the pipe sections together. When slip-joint pipe is installed above the ground, it should be provided with hooks or lugs for wiring or bolting the sections together to prevent them from pulling apart during temperature changes.

Since welded steel pipe is fairly thin as compared with other types, it should be protected against corrosion. The protection most commonly used is an asphalt or tar coating, both outside and inside. Additional protection usually consists of a wrapping; several grades are available. The type most suitable for the particular soil conditions should be selected. Welded pipe is sometimes galvanized. Although effective on the inside, and on surfaces exposed to the atmosphere, galvanizing protects for only a short time on the outside of pipe in contact with the soil. Under some conditions "cathodic" protection may be desirable.[6]

Standard pipe with screw joints, used primarily for lines not exceeding 4 inches in diameter, is available either plain (black) or galvanized. Plain-end line pipe for welding or coupler connections is available in many sizes and weights ranging from 2⅜ to 24 inches outside diameter (O.D.). Wall thicknesses range from approximately that of Merchant casing to that of extra strong pipe.

Merchant casing, available in sizes ranging from 2¼ to 16 inches, O.D., differs from standard pipe in being lighter in weight and in having a finer thread. Casing may be connected either by threaded couplings or by welding. Ordinary fittings, threaded for casing, are available. Connections to valves and special fittings are made with flanges or by welding standard pipe nipples to the casing and using standard screw fittings. Casing is usually installed with only an asphalt-dip coating or none.

Old pipe, casing, or boiler tubing, reconditioned, is used to some extent, especially for orchard systems in southern California. Usually it costs less than any other pipe. Threaded joints are sometimes used, but more often the joints are welded. Used pipe is reconditioned by cleaning it to remove rust and scale; defective sections are cut out, and an asphalt-dip coating applied. Although the economy of reconditioned pipe may be questioned, since there are no definite standards regarding its exact condition when installed, it has often proved satisfactory. Where soils are only slightly corrosive, it sometimes lasts fairly well. Its low cost has been particularly attractive to farmers.

Plain concrete pipe as ordinarly used for irrigation systems lacks strength to withstand the pressures required for sprinkling. Maximum recommended working heads for concrete pipe range from about 20 feet for large sizes to 50 feet for 6-inch pipe. It is suitable only for the so-called "low pressure" sprinkler systems, and for lines supplying water to pumping plants. Reinforced concrete pipe, however, can be made that will withstand pressures adequate for sprinkling systems. Such pipe has been used in some sections of California for irrigation systems, although

[6] For a complete treatment of soil corrosion and pipe-line protection, see: Ewing, Scott. Soil corrosion and pipe line protection. 277 p. American Gas Association, New York, N. Y. 1938.

very seldom in connection with sprinkling. In 12-inch and larger sizes it is probably less expensive than steel lines and in addition is more permanent.

Hydrants.—With stationary pressure supply lines, hydrants or valves must be spaced at convenient intervals along the line. The usual arrangement (fig. 13) shows the hydrants spaced three times the distance between portable lines so that each hydrant is used for three positions of the portable line. In orchards, hydrants are usually spaced at every second, or every fourth tree row. These hydrants commonly consist of a short length of standard pipe and a valve. When welded steel lines are used, the risers are usually welded to the line. Threaded tees in the line are ordinarily used for risers on screw pipe.

Several different types of valves are suitable for hydrants. For small sizes (3 inches or less) angle valves may be used; for hose connections the garden-type angle valve with hose thread is suitable. For larger sizes, gate valves are used almost exclusively. Valves are sometimes fitted with quick-couplings for connection to the portable sprinkler lines, though in many cases a portable fitting with quick-coupling is moved with the portable line and screwed into the valve before the connection is made. This arrangement eliminates a large number of special couplings and somewhat reduces the installation cost.

To economize risers are sometimes provided with screw caps, and only a limited number of valves are used. These valves are then changed about once a day to the risers that will be needed for that day's operation. Although this plan reduces the initial cost, it makes operation somewhat less convenient, and necessitates shutting down the pumping plant while the valves are changed.

LOW-PRESSURE SYSTEMS FOR FIELD CROPS

Most of the sprinklers used for portable systems except under-tree orchard systems, operate best at pressures above 30 pounds per square inch. With lower pressures, the distribution is usually less uniform. Some sprinklers, however, distribute water satisfactorily at fairly low pressures (10 to 20 pounds per square inch). As previously mentioned, the area covered by a sprinkler increases with pressure up to a certain point; and, therefore, higher pressures permit wider spacings of sprinkler lines with less frequent moves. High pressures also break up the jet into finer drops, which have less tendency to puddle the soil, and which permit higher rates of application. High pressures also make possible the use of smaller pipe sizes—an important feature. When the pressure is low, it is difficult to maintain uniform discharges from sprinklers along the line, especially on hillsides. Despite these disadvantages,

there are conditions under which low-pressure systems are desirable. Since the power requirement and the cost of pumping are approximately proportional to the pressure, the minimum pumping cost results with the lowest pressure that is otherwise satisfactory. Investigation indicates, however, that the power cost for pumping is usually only a small part of the total cost of operating sprinkler systems. Probably more important than the cost of pumping is the fact that the lower pressure permits larger-capacity systems to be used with a given power unit, and this may appreciably lower the cost per unit of water applied, especially if the larger system can be handled without an increase in labor cost.

Sometimes pressures of 10 to 20 pounds per square inch can be developed by gravity, whereas higher pressures would require pumping. Sprinkling systems that can operate at these low pressures might be feasible where those requiring higher pressures would not. Even though the distribution of water with such systems might be less uniform than with higher pressures, it might be better than with surface irrigation. To meet these requirements, various types of low-pressure systems have been developed. Some sprinklers operating at 15 pounds per square inch can be spaced 40 to 50 feet apart. Low-pressure systems using sprinklers of this type resemble in many respects the higher-pressure systems.

PERFORATED PIPE SYSTEMS

Another kind of low-pressure system consists of lightweight, perforated pipe that distributes water fairly uniformly over a strip of ground along the line. This pipe is available in two types having rates of application of about 1 inch and 2 inches per hour, respectively. An interesting feature is that the actual rate of application for either type remains approximately constant, while the effective width of the strip covered varies with the pressure from about 20 feet at pressures as low as 4 or 5 pounds per square inch to about 50 feet at a pressure of 20 pounds per square inch. In comparison with systems using rotating sprinklers, perforated pipe systems have relatively high rates of application which necessitates frequent moves of the pipe and may require the operator to devote full time to this task. The alternate-line arrangement, permitting continuous operation, is especially desirable. Because of its light weight the pipe can be readily moved by one man. There is also the advantage that a relatively large area can be irrigated with a short length of pipe.

Perforated lines are used principally for irrigating pastures and other low-growing crops. The high rates of application make them most suitable on pervious soils, or where only light applications are desired. Since it is not possible to regulate and equalize the pressure along the line as

with sprinklers, it is especially important that the system be arranged, when possible, so that the line is along the contour rather than up and down the hillside.

TRAVELING SPRINKLER MACHINES

To reduce the cost of sprinkling by reducing the amount of labor required for operating the system, several growers in California have constructed traveling sprinkler machines that pump water from a ditch

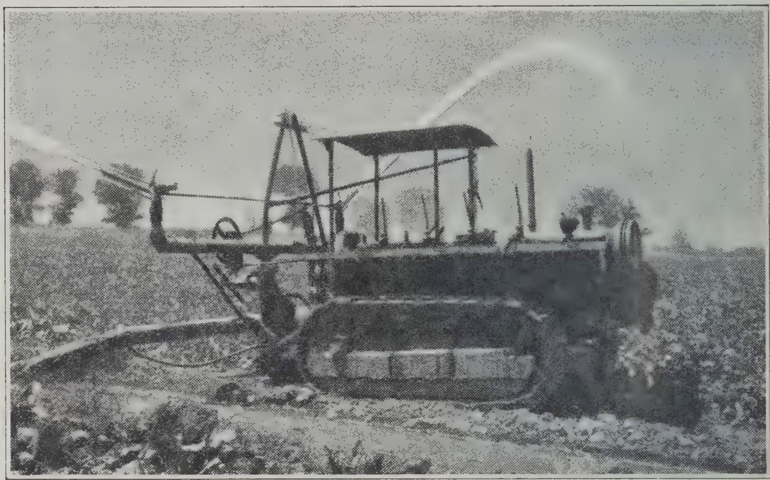

Fig. 17.—Traveling sprinkler machine in operation. This machine moves continuously along the ditch at a speed of 75 feet per hour. Two sprinklers discharge about 500 gallons per minute under pressure of 60 pounds per square inch and effectively cover a strip 250 feet wide. The average application is about 2½ inches.

and distribute it through large sprinkler nozzles while moving slowly but continuously along the ditch. These machines are planned for one-man operation. Figure 17 shows an example. The capacity of these machines varies from about 400 to 800 gallons per minute. Most of them have been built on a tractor geared down to move 1 to 5 feet per minute with the engine operating at normal speed. To obtain maximum coverage and to break up the jets from the large nozzles into a spray, pressures of 60 to 80 pounds per square inch are used. According to field tests on two of these machines, they cover effectively a strip about 250 feet wide. They require, therefore, the construction of ditches at this spacing throughout the field, a feature which limits their use to rather flat areas where such ditches are feasible. These ditches remove about 5 per cent of the area from cultivation.

Since portable pipe is not required, the cost of constructing such a machine is generally less than the cost of an ordinary portable sprinkler system of similar capacity. The cost of power for pumping is normally higher than for other systems because of the higher pressure required. For comparison, the total operating cost should include the cost of constructing the ditches plus the crop value on the land removed from cultivation.

TABLE 1

SPRINKLER DISCHARGE REQUIRED FOR VARIOUS APPLICATIONS OF WATER IN A TWELVE-HOUR PERIOD

Sprinkler spacing, feet	Discharge, in gallons per minute, for various depths of application*									
	1.0 inch	1.5 inches	2.0 inches	2.5 inches	3.0 inches	3.5 inches	4.0 inches	4.5 inches	5.0 inches	6.0 inches
16 by 16	0.22	0.33	0.44	0.55	0.67	0.78	0.89	1.00	1.11	1.33
18 by 18	0.28	0.42	0.56	0.70	0.84	0.98	1.12	1.26	1.40	1.68
20 by 20	0.35	0.52	0.69	0.87	1.04	1.21	1.38	1.55	1.73	2.08
22 by 22	0.42	0.63	0.84	1.05	1.26	1.47	1.68	1.89	2.10	2.51
24 by 24	0.50	0.75	1.00	1.25	1.49	1.74	1.99	2.24	2.49	2.99
26 by 26	0.58	0.88	1.17	1.46	1.76	2.05	2.34	2.64	2.93	3.51
28 by 28	0.68	1.02	1.36	1.70	2.03	2.37	2.71	3.05	3.39	4.07
30 by 30	0.78	1.17	1.56	1.95	2.34	2.73	3.12	3.51	3.90	4.67
35 by 35	1.06	1.59	2.12	2.65	3.18	3.71	4.24	4.77	5.30	6.35
40 by 40	1.38	2.08	2.77	3.46	4.16	4.85	5.54	6.23	6.92	8.31

* Average net application for the square area served by each sprinkler.

UNDER-TREE SPRINKLER SYSTEMS FOR ORCHARDS

Under-tree sprinkler systems have become very popular in some areas. Most of these systems are portable or semiportable. Essentially they consist of small, low-capacity sprinklers mounted on short risers that are located in the area between adjacent trees. The sprinklers are usually spaced the same distance apart as the trees so that each sprinkler covers an area equal to that occupied by one tree. Three different types are used for this purpose: whirling sprinklers; small, slow-revolving sprinklers; and fixed sprinkler heads of the type used for concealed lawn-sprinkler systems.

Sprinklers for Under-Tree Systems.—One problem in developing this type of system has been to obtain a satisfactory sprinkler. To facilitate the moving operations and to obtain adequate penetration without run-off, these systems are sometimes operated on a 12-hour schedule, the sprinklers being moved morning and evening (6 a.m. and 6 p.m.). For the usual applications desired, this requires a sprinkler of rather low capacity, discharging 1 to 3 gallons per minute. There has been some

difficulty in obtaining sprinklers of these low capacities that perform properly. Rotating and whirling sprinklers of low capacities are not always dependable, for occasionally they fail to rotate. Also, because of the very small nozzles required, clogging is a problem. With the fixed sprinkler heads, it is difficult or impossible to secure the desired coverage without increasing the capacity beyond that desired. Most of the fixed

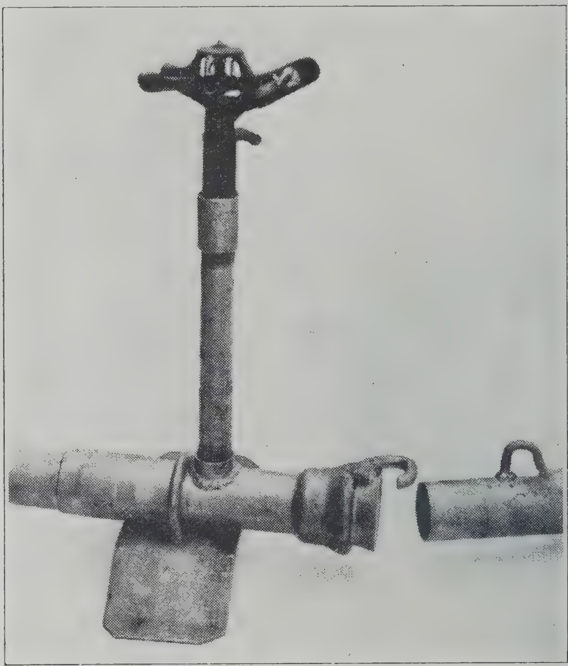

Fig. 18.—Portable sprinkler unit illustrating small-sized sprinkler pipe and typical sprinkler. The pipe is made from 1½-inch, O.D., 18-gauge steel tubing, galvanized after fabrication. It comes in standard lengths of 20 feet with a ½-inch outlet on each length. Other lengths are also available.

sprinklers, such as lawn-sprinkler heads have, for example, capacities between 2 and 3 gallons per minute at 20 pounds' pressure, and are designed to cover effectively areas 12 to 16 feet square. Most tree spacings are 20 feet or more, and sprinkler capacities of only 1 to 2 gallons per minute are desirable. Fixed sprinklers that will effectively cover areas 20 feet square usually have capacities of 4 to 8 gallons per minute. They are suitable, therefore, only on pervious soils and where sprinklers are to be moved at frequent intervals. Table 1 gives the discharge required for average applications of 1 to 6 inches in depth over square areas 16

to 40 feet on a side in a period of 12 hours. This table covers the usual range of tree spacings in orchards and assumes that sprinklers are to be spaced the same distance as the trees—that is, the sprinkler is to be located in each square between four adjacent trees. For the usual tree spacing of 20 feet, an application of about 4 inches requires a discharge of only 1.4 gallons per minute. This table can be used for other periods of operation by simply increasing or decreasing the discharge accordingly. If, for example, sprinklers are to be moved at 4-hour intervals,

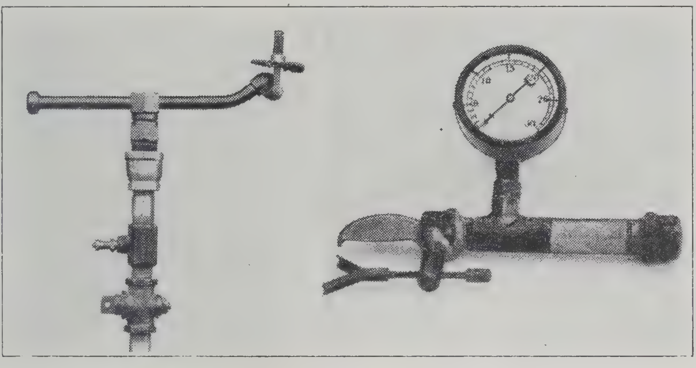

Fig. 19.—Methods of determining and regulating the pressure at sprinklers. At the left is shown a sprinkler riser equipped with shut-off cock and "tank valve" which permits individual regulation of sprinklers. At the right is a homemade Pitot gauge for determining the pressure at the tip of a nozzle. The tip of the gauge is held in the center of the jet about half the nozzle diameter from the end of the nozzle, and the pressure, corresponding to the velocity head, is read on the pressure gauge.

three times the discharge given is required. From table 3 one can determine the approximate nozzle sizes for these discharges. Some orchard sprinklers have two nozzles, and others have only one.

Portable Sprinkler Pipe for Under-Tree Systems.—Because of the low capacity of under-tree sprinklers, sprinkler pipe in relatively small sizes is suitable. Such pipe is now available in 1½- and 2-inch diameters. It is made from 18-gauge tubing and has special quick-couplings (fig. 18). Although ordinarily furnished in 20-foot lengths, other lengths can be obtained on special order. Pipes of the same length as the tree spacing are preferable. Special quick-couplings are also available for other kinds of pipe, including lightweight electric conduit and hard-temper copper tubing. Before the regular sprinkler pipe was available in small sizes, many systems were made up from 1-inch and 1¼-inch electric conduit (sometimes called electrical metallic tubing). This tubing is available in 10-foot lengths in sizes ranging from ½ to 2 inches. Inside diameters are slightly greater than the nominal sizes. It is available galvanized

inside and outside or with an electroplated galvanizing on the outside and lacquer finish on the inside. One objection to its use is that welding or brazing the short lengths together destroys the protective finish on the inside.

Sprinklers are mounted on ½-inch pipe risers 6 to 18 inches long, the length depending upon whether or not a summer covercrop is grown in the orchard. Risers should be as short as possible, since high risers tend to overturn the pipe.

Where there is an appreciable variation in elevation along a sprinkler line, or where there is excessive variation in pressure due to friction loss, a shutoff cock on each riser, and some method of determining the pressure, make it possible to regulate and equalize the pressure at the sprinklers. One method is to use a small "tank valve," similar to an automobile-tire valve stem, between the shutoff cock and the sprinkler (left view, fig. 19). Pressures can then be determined with a pressure gauge equipped with an air-hose chuck. With some sprinklers, pressures can be determined with a Pitot gauge (right view, fig. 19). A whirling sprinkler is now available which automatically maintains a constant discharge for all pressures above 8 pounds per square inch, and eliminates the necessity for manual regulation.

The size of sprinkler pipe required for under-tree systems depends upon the capacity and spacing of the sprinklers and upon the length of the portable laterals. Where no pressure regulation is provided, the pipe should be large enough so that the friction loss in the pipe will not exceed 20 per cent of the average pressure; this will limit the variation in discharge of the sprinklers to 10 per cent. The permissible length of pipe in different sizes for different sprinkler discharges can be determined from figure 26.

In small orchards one main supply line through the center with portable laterals extending halfway across the orchard is the simplest arrangement. For large orchards, it is sometimes more economical to use two parallel supply lines with shorter laterals, which will permit the use of smaller portable pipe. One can determine the most economical arrangement only after ascertaining what sizes of pipe are required under both plans.

When sprinklers are moved only twice a day, two tree spaces can be covered with each lateral per day, and the total number of laterals required for the orchard is determined by the required frequency of irrigation. Most orchards will require two or more portable laterals.

Stationary supply lines should be of ample capacity to carry the total flow with a reasonable friction loss. Pipe of minimum size can be used when the laterals are distributed throughout the orchard and arranged

so that each takes care of the contiguous areas. Figure 20 shows a suitable arrangement for a 10-acre orchard. Friction losses in different types of pipe suitable for stationary lines are given in tables 5 and 6 and in figure 24.

Under-Tree Systems Using Sprinklers Attached to Hose.—Many under-tree sprinkler systems consist of several sprinklers mounted on

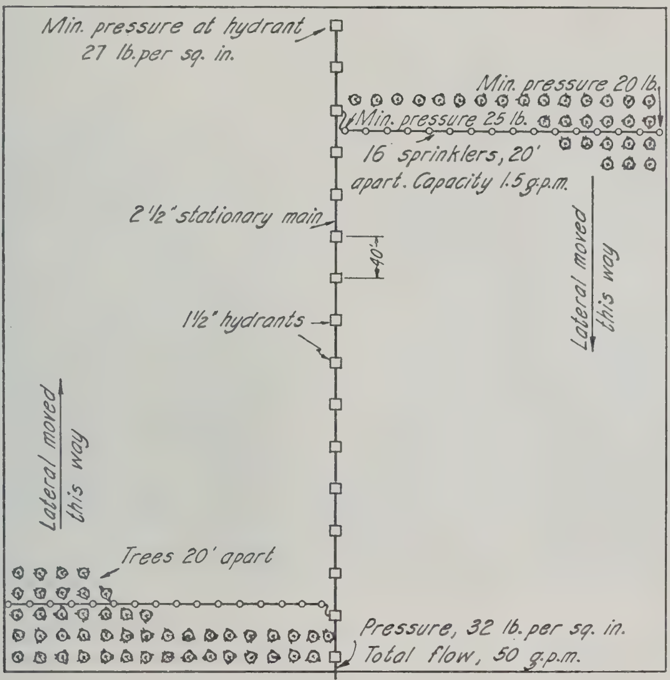

Fig. 20.—Arrangement of portable under-tree sprinkler system for 10-acre orchard.

small stands joined with short sections of hose (fig. 21). One-inch or ¾-inch garden hose is used for this purpose. Friction loss in hose of this size is relatively high (table 9), as compared with pipe. This usually limits the number of sprinklers that can be operated on each line to three or four, according to the sprinkler capacity.

Hose systems are generally less desirable than those using metal pipe. They require closer spacing of supply lines or the use of a long length of supply hose so that several sprinkler settings can be made from the same hydrant. When long hoses are used, a considerable friction loss must be overcome by pumping against higher pressures. Hose systems are less convenient to move than pipe systems, and the relatively short

life of the rubber makes them fairly expensive. Until recently, sprinkler pipe in small sizes was not available.

Portable Drag-Type Sprinkler Systems for Orchards.—Under-tree sprinkler systems in which the units are moved by dragging lengthwise have been used in some parts of California for several years. They were developed to reduce the labor required for moving portable equipment. They are of two general types—those in which the units are dragged

Fig. 21.—Under-tree sprinkler system consisting of three small lawn sprays connected together with 20-foot lengths of ¾-inch garden hose. The entire unit is moved from one supply lateral to another by dragging lenghtwise.

with a tractor or other source of power, and those in which they are moved by hand. In the first type, the weight of pipe is not especially important; standard pipe, boiler tubing, or casing can be used. One system of this type used 2-inch O.D. boiler tubing welded into units 52 feet long (for 26-foot tree spacings) connected together with 1½-inch standard pipe couplings, short nipples of 1½-inch pipe being welded to the ends of the tubing. This system has been operated with as many as sixteen sprinklers spaced 26 feet apart on each lateral, although shorter laterals with eight sprinklers proved more satisfactory. The head end of the line is provided with a wheel cart to hold the risers vertical while they are being moved. Pipe is moved with the same tractor used in cultivating the orchard. This system is operated on a 12-hour schedule, moves being made morning and evening.

For many orchards, however, it is more convenient to use smaller units of such size and weight that they can be moved by hand. One system of this type utilizes electrical conduit tubing connected together with a special quick-coupling developed for the purpose. Units containing three or four 20-foot lengths, with a sprinkler mounted on each, can be dragged by hand. One principal advantage of systems of this type, is that one need not walk on wet ground to move the pipe.

A portable drag-type unit consisting of ¾-inch type M copper tubing has been developed for the University of California experimental orchard at Paradise, California. This unit is 120 feet long, permanently connected together with solder fittings. It contains seven sprinklers 20

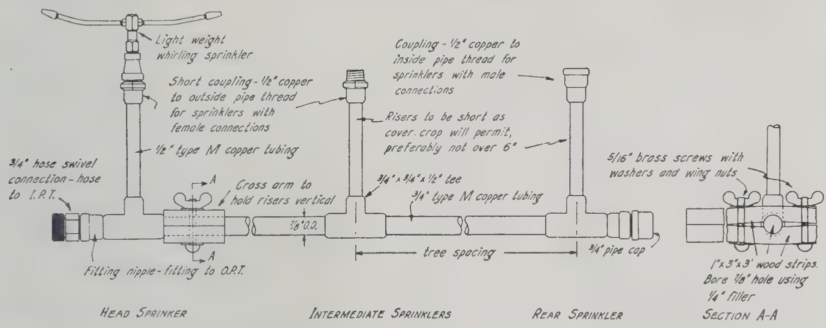

Fig. 22.—Details of portable drag-type sprinkler unit made from copper tubing. Either type of riser shown may be used, according to the type of sprinkler.

feet apart, mounted on short risers of the same material. Figure 22 shows the details.

This hard-temper tubing, a relatively new product, is available in all standard pipe sizes from ¼-inch to 12-inch diameters. Its rigidity and its light weight, together with its natural resistance against corrosion, make it ideal for portable sprinkler units. The ¾-inch tubing has a wall thickness of 0.032 inch and weighs only 0.328 pound per foot. All sizes come with outside diameters ⅛ inch greater than the nominal size; thus ¾-inch tubing is ⅞ inch O.D. (outside diameter) and 0.811 inch I.D. (inside diameter).

The Paradise units are connected to hydrants on a stationary supply line with a 25-foot length of ¾-inch hose. The risers are held in a vertical position by an adjustable wooden crossarm (at the head end), so they can be kept vertical regardless of the cross slope. Brass or galvanized bolts with wing nuts should be used in the crossarm, for iron bolts will rust quickly under the sprinklers. The unit is designed to be operated on a 12-hour basis and to be moved night and morning. The sprinklers have a capacity of about 1.4 gallons per minute at 20 pounds' pressure,

which provides an average application of about 4 inches in a 12-hour period with sprinklers spaced 20 feet apart.

The operator moves the unit from one position to another by dragging it forward, holding the sprinklers in a vertical position with the cross-arm. With a main supply line every 140 feet, the hose can be left attached to the unit. Where the supply lines are spaced twice the length of the unit, the hose has to be alternated from one end of the unit to the other. In this case, each end of the copper-tube unit should be equipped with a swivel hose connection, and one end plugged, to eliminate the necessity of exchanging the positions of the hose connection and the pipe cap for each move. One extra plug for the hose connection will simplify the moving.

When the unit has completed the last setting in a row, it is moved to the next row in much the same manner as a freight train is switched from one track to a parallel track. For alternate middle irrigation it is switched over two tree rows. The tubing, being somewhat flexible, can be dragged around a curve without injury. If bent too sharply, however, it will kink. One-inch tubing is more satisfactory in this respect. Care must be exercised, in moving from one row to another, to prevent the sprinklers from catching on tree limbs.

Although the unit is easily moved from one tree row to another in a deciduous orchard, difficulty might be encountered in a citrus grove because of the low branches. This could be overcome, however, by using standard pipe nipples for risers so that the risers and the sprinklers can be removed before a change from one tree row to another. The use of tee fittings with threaded side outlet eliminates the need for special couplings at the top of the risers.

For winter storage the unit can be placed beside a fence, where it will be out of the way and protected from damage. Since the entire unit is of copper and brass, it will not corrode.

Copper tubing has been used for a portable sprinkler system by one grower in southern California since 1938. It is ideally adapted to drag-type units because it weighs less and has a higher permanent carrying capacity than steel tubing. It requires no special protective coating, such as the galvanizing that adds materially to the cost of sprinkler pipe made from steel tubing. The drag-type system has the further advantage of eliminating the need of quick-couplings. It is therefore less expensive than most other portable sprinkler systems for orchards. Wear on the bottom of the units is excessive in some places, especially on gravelly soils.

A field test at Paradise indicated that the pull required to drag the unit complete with the hose on wet ground was about 50 pounds.

SPRINKLING COMPARED WITH OTHER METHODS OF IRRIGATION

Many claims made for sprinkling are not substantiated by facts or have little practical significance. Sprinkling has, however, certain definite advantages, some of which apply only under specific conditions.

Advantages of Sprinkling.—As was mentioned earlier, sprinkling differs fundamentally from surface irrigation in that it distributes water to the soil independently of the soil itself. With all methods of surface irrigation the soil is the final medium for distributing the water, which is either flooded over the surface or run in furrows spaced close enough together so that most of the soil can be moistened. A large part of the water applied may be lost by deep percolation, especially on pervious soils with sandy or gravelly subsoils. Any soil can be sprinkled without excessive waste. Unless the fields are properly graded and the irrigation system carefully laid out, uniform distribution by surface methods is difficult to obtain.

Sprinkling can sometimes be considered as crop insurance. During spring months when drying north winds are common, crops are frequently lost, or poor stands are caused by poor germination. Frequent light applications at this time have beneficial results. Unless the crop is planted in rows on raised beds, surface methods of irrigation are not suitable for this purpose.

Frequently it is claimed that by sprinkling, one can obtain the same penetration with less water. Extensive investigations have demonstrated, however, that a certain amount of water is required for a given penetration regardless of the method. The moisture content of the soil must be raised to the field capacity[7] before further downward movement results. Field capacity is the moisture percentage of the soil on a dry-weight basis a few days after an irrigation or heavy rain, and is therefore the approximate amount of moisture the soil will retain against the downward force of gravity. Where a better penetration is apparently secured with lighter applications by sprinkling, the water is simply more uniformly distributed over the field and less is wasted. Excessive amounts are not applied in low spots, and loss by runoff can be avoided.

Sprinkling eliminates many field ditches and permits the planting of almost the entire acreage. Dispensing with ditches may in turn lessen the weed problem. It also facilitates cultivation, making possible the working of larger blocks.

[7] For further discussion of field capacity and other terms relating to soil moisture see: Veihmeyer, F. J., and A. H. Hendrickson. Essentials of irrigation and cultivation of orchards. California Agr. Ext. Cir. 50:1–24. Revised, 1936. (Out of print.)

Under some conditions, sprinkling has proved beneficial in controlling certain insect pests. In the Sacramento Valley it apparently aids in controlling thrips[8] and red spider on beans, and probably helps control both these pests on other crops. There is also some evidence that it reduces the number of aphids on peas. Usually, however, it cannot be considered a complete control; and where spraying or dusting is required, sprinkling may be detrimental because it tends to wash the residue from the plants.

In the state of Washington[9] sprinkling was found to have no value in the control of codling moths on apple—as believed by some growers; instead, it interfered with the control by spraying. An average of 29 per cent of previously applied arsenate of lead on apples was removed with each sprinkling. The investigators also concluded that sprinkling did not affect aphid infestation and leafhopper injury, though it did aid in the control of red spider. Apparently, too, it was detrimental in connection with most apple diseases, such as perennial canker fruit rot, pear blight, and downy mildew.

Portable sprinkler systems provide an economical method of applying fertilizers in solution. The usual procedure is to dissolve a bag of fertilizer in a barrel of water and introduce it into the sprinkler system through a 1-inch hose connected to the suction side of the pump during the first part of a run. Since the subsequent application of fresh water completely washes the fertilizer solution from the foliage, no burning results. Ammonium sulfate and calcium nitrate have both been successfully applied in this manner. Some of these materials, especially ammonium sulfate, are corrosive to metals and one should be careful regarding their use, and especially to see that the system is thoroughly flushed out after use. Frequent inspection of the pump and of the inside of the pipe is suggested.

On land with rough or irregular surface features, sprinkling eliminates the grading and leveling that would be required for surface irrigation. On shallow soils, especially those underlaid with hardpan, the removal of a few inches of surface soil may be very detrimental. Under such conditions, extensive leveling is not practicable, or, even where it is feasible, a sprinkler system might cost less than such land preparation. Tenant farmers would rather buy portable equipment than spend an equivalent amount to level land they do not own.

In some parts of California sprinkling is used primarily as a protection against erosion. Where orchards have been planted up and down hillsides, furrow irrigation down the slopes is often the only practicable

[8] Bailey, Stanley F. The bean thrips. California Agr. Exp. Sta. Bul. **609**:1–36. 1937.

[9] Overley, F. L., *et al.* Irrigation of orchards by sprinkling. Washington Agr. Exp. Sta. Bul. **268**:1–50. 1932.

method of surface irrigation. The result, frequently, has been excessive erosion. Sprinkling combined with permanent covercrops may effectively prevent further loss of soil. Although contour furrows can be used for irrigating hillside orchards, that method necessitates planting the tree rows on contour grades and is therefore not suited to orchards planted in straight rows.

Conditions Favorable to Sprinkling.—Sprinkling may be an economical method of irrigation because of a low annual water requirement. With portable systems the cost is primarily that of operation; and where the annual water requirement is low, sprinkling may cost less per acre than suitable methods of surface irrigation involving heavier applications of water. In the Sacramento Valley for example, a spring crop of peas may require only one light application, which might be made more cheaply by sprinkling than by surface methods.

In the San Joaquin and Sacramento Delta, and along the Sacramento River, sprinkling has found rather extensive use on areas where the water table is close to the surface—that is, within 2 to 4 feet. In this area the general slope is slight, but undulation of the ground makes surface irrigation very difficult unless the land has been properly graded. Because of the high water table, a continuous upward movement of water by capillarity partially satisfies the crop requirements. Without irrigation, however, the upper 6 to 12 inches of soil usually gets dry, and some crops suffer. Only light applications are required, however, to moisten the surface soil; and when surface irrigation is attempted, the heavier applications required may temporarily waterlog the soil, with detrimental results. Before the introduction of portable sprinkler systems, subirrigation was the method most commonly practiced. Water was distributed to parallel ditches, or narrow trenches called "spud ditches," spaced 50 to 200 feet apart, and was allowed to run until the surface of the soil between the ditches appeared moist. As a result, the water table was raised temporarily until all the soil above it was moistened by capillarity. Subirrigation has several disadvantages. As a result of evaporation and transpiration, salts are continuously moved upwards and concentrated in the surface soil. When this effect is not offset by adequate leaching during the winter, a detrimental saline condition may develop. Also, because of the high water table maintained to make subirrigation feasible, the rooting depth is restricted; better yields could probably be obtained if the water table were kept lower. By sprinkling, light but adequate amounts can be applied, and the surface soil kept moist. Under these conditions the total annual water requirements are low, usually less than half of what would be needed under similar climatic conditions without the high water table; and the cost of sprin-

kling is not excessive even though the cost per acre-inch of water might be high.

Sprinkling is also adapted to conditions where a shallow soil is underlaid by either hardpan or gravel. With hardpan, because of the lighter applications and more uniform distribution of the water, temporary waterlogging can be avoided; and with gravel, excessive losses of water and leaching can be prevented.

Sprinkling is a desirable method of irrigation in certain coastal areas where, because of moderate temperatures and high relative humidities, the seasonal water requirements are low. In many such areas, rolling and sloping ground makes surface irrigation somewhat difficult and expensive.

Limitations of Sprinkling.—From the foregoing, it must not be inferred that sprinkling is undesirable where surface methods of irrigation are practicable. Sprinkling can be satisfactory under practically all conditions although it is not always advisable. As compared with surface irrigation, however, it offers few advantages in many places and generally costs more. When fields are properly prepared for surface irrigation, and where one irrigator can manage fairly large streams, the cost of application by surface methods will usually be less than 25 cents per acre-inch of water—sometimes as low as 5 or 10 cents. Sprinkling, on the other hand, nearly always costs more than 50 cents per acre-inch for labor and power and frequently more than $1.00, exclusive of interest and depreciation. The total cost, including interest and depreciation, and cost of water, varies greatly and is difficult to determine because of the uncertainty as to the life of portable sprinkler equipment. Also, because engines used for pumping generally serve other purposes as well, only an arbitrary proration of cost can be made.

Besides the higher cost, other factors limit the use of sprinkler systems. Some soils absorb water so slowly that adequate applications by sprinkling are not feasible; only light applications can be made before water accumulates on the surface. As a result, frequent irrigations are necessary, with relatively greater evaporation losses and generally higher costs than if heavier and less frequent applications were possible. With light applications adequate penetration can be secured only by irrigating while the soil still holds an appreciable amount of available moisture. When water penetrates to only a shallow depth and the soil below this depth dries out, the available soil nutrients are not utilized effectively. During one season the writer observed the use of a portable sprinkler system on a field of sugar beets on a deep loam soil that requires about 8 inches of water to wet the soil to a depth of 6 feet when dried to the permanent wilting percentage. The winter rainfall was subnormal, and

only about 2 feet of soil was wet at the beginning of the growing season. When irrigation started, the crop had extracted practically all available moisture and was showing definite signs of wilting. The owner thought best to hurry over the field before the crop was permanently damaged. The sprinkler system, consisting of a line of 4-inch portable pipe with sprinklers discharging about 20 gallons per minute mounted 40 feet apart along the line, was operated in one position for about 2 hours, when water would begin to accumulate on the surface. As this method of operation resembled one which had proved successful in the nearby Delta region, the owner was apparently following an established practice. Soil samples taken at weekly intervals to determine the moisture conditions indicated that penetration below about 18 inches was not obtained at any time during the season. In many places the penetration did not exceed 12 inches. The system could not cover the field rapidly enough to prevent the beets from wilting between irrigations. After each application, new leaves would sprout out and grow vigorously; but soon these would wilt, or even die and fall off. The yield was poor in comparison with that previously obtained with surface irrigation. After one season's trial sprinkling was abandoned. The writer believes, however, that satisfactory results could be obtained on this soil with a sprinkler system of sufficient capacity provided water was applied slowly enough to permit adequate penetration. Investigations with sugar beets under similar conditions show that two or three heavy surface applications, wetting the soil to a depth of 6 feet, are sufficient and produce good yields.

On some soils pipe cannot be moved immediately after a heavy application, because the ground becomes too soft on which to work. Light applications that permit immediate removal of the pipe are generally made. Where feasible, a better solution is to use the alternate-line arrangement and allow the pipe to remain on the wet ground for several hours before moving it. When the system is of sufficient capacity to take care of the field if operated only at night, the pipe can be left in place until the following evening and then moved for another run. This permits the soil to dry enough to facilitate pipe moving. These methods require, of course, relatively greater investments in equipment.

As previously mentioned, sprinkling sometimes spreads plant diseases, and makes difficult the control of some insect pests. For some crops, sprinkling cannot be used for these reasons.

COST OF SPRINKLING

When considering a sprinkler system, one must weigh all possible benefits, together with the relative costs of sprinkling and other methods. As mentioned above, advantages are sometimes, but not always, obtained

from sprinkling. The farmer's individual problem must be considered. The benefits in his specific case might include, for example, a saving of water, insect control, higher yields, reduced cultivation costs. To apply monetary values to these results is difficult or impossible without specific information regarding the success of other sprinkler systems in the vicinity.

The annual cost of sprinkling, which includes interest and depreciation on the investment, and operating costs, can be estimated for specific conditions. The first step is to determine the initial cost, the investment in equipment and installation. One can plan a system and then have figures quoted by manufacturers, dealers, or contractors, or one can obtain the services of an engineer experienced in these matters. Some companies offer excellent engineering service and, given the necessary information, will plan an economical layout and submit cost figures.

Depreciation and Interest on Investment.—The annual depreciation should be figured separately for the different items making up the system. The useful life and proper rate of depreciation applying to underground stationary pipe will depend upon the corrosiveness of the soil and upon the type of pipe used. Experience of water companies and other utilities in the area may be drawn upon. Since portable sprinkler pipe is relatively new, little experience data are available. Some of this pipe in use for about ten years is still in good condition. A life of ten to twenty years can be assumed for estimating depreciation. Sprinklers generally last a much shorter time than pipe and sometimes require frequent replacement of wearing parts. The life of different kinds of sprinklers vary; some have been completely worn out in less than one season on portable systems. Specific information on the durability of the particular make being considered might be obtained from other users, or from manufacturers or dealers. Generally speaking, an annual depreciation rate of about 25 per cent would be a fair estimate for sprinklers. The proper rate of depreciation to apply to the pumping plant is questionable. Where tractors are the source of power, they are generally used for other purposes during part of the year. The depreciation chargeable to sprinkling will depend upon the relative use made of the tractor for other purposes. A good pump has a life of at least ten years. Electric motors, when not overloaded, are probably good for at least twenty years.

In addition to depreciation one should include interest on the investment. Whether this should be figured at the rate one would have to pay or at the rate he would receive on money invested will depend on the individual case.

Cost of Operation.—Ordinarily the per-acre cost of portable sprinkler systems is not high, and the total annual cost of sprinkling is not ap-

preciably affected by the interest and depreciation rates applied. The principal cost is that of operation. In some instances, the annual operating cost exceeds the total investment in the system. The operating cost can be divided into two principal items: the power cost, including the fuel, lubricating oil, and other materials required by the pumping plant; and the labor cost, for handling the system. In most cases the labor cost is the principal item, sometimes four or five times higher than the power cost.

Many systems with portable pumping plants are operated continuously day and night, with two crews of two or three men, working 12-hour shifts. These operators do nothing but take care of the sprinkler system. The cost per acre-inch of water can be determined by dividing the total daily operating cost by the number of acre-inches of water applied. Assume, for example, that a system has a capacity of 500 gallons per minute, that it is moved at 4-hour intervals, and that ½ hour is lost at each move. The net daily operating time is therefore 21 hours. Remembering that 450 gallons per minute is equivalent to 1 acre-inch per hour, the total amount of water applied per day would be:

$$\frac{500 \times 21}{450} = 23.3 \text{ acre-inches.}$$

Suppose that the system operated in the usual manner with two men during the daytime and two men at night, at a daily wage of $4.00, or a total of $16.00 per day for labor. Assuming the fuel for pumping costs $4.00, and the lubricating oil and grease costs 50 cents, the total daily operating cost would be $20.50, or 88 cents per acre-inch of water applied, of which 19 cents is for power and 69 cents for labor. If this system was used 100 days during the season, the annual operating cost would be $2,050, which would probably exceed the cost of the system, exclusive of the tractor. These figures would be typical for many of the portable sprinkler systems in the Sacramento Valley.

Where a sprinkler system can be operated in such a way that the pipe need be moved only twice a day, and especially where continuous attention is not necessary, the labor cost properly chargeable to the system may be less than half of that given above.

In the summer of 1935 and 1936, field studies were made to obtain some actual data on costs. The sprinkler systems studied were in the Sacramento Valley and were all operated with portable pumping plants. Tests were made to determine the capacity of the systems, and information regarding the amount and cost of fuel and lubricating oil used and wages paid was obtained from the operators or owners. From these data the operating cost per acre-inch of water applied was calculated. Results

TABLE 2

RESULTS OF FIELD STUDY TO DETERMINE COST OF OPERATING PORTABLE SPRINKLER SYSTEMS IN SACRAMENTO VALLEY

System no.	Length of portable pipe, feet*	Number of sprinklers	Minimum and maximum pressure at sprinklers, pounds per square inch	Pump discharge, gallons per minute	Total head, feet	Acres covered per day	Average depth of application, inches	Total application, acre-inches per day	Efficiency of system per cent	Net operating time, per cent	Average daily wage, dollars	Approximate operating cost per acre-inch of water applied, dollars		
												Labor	Power	Total
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Split-line arrangement; tractors using stove oil														
1	1,760	44	24–32	680	80	13.4	2.4	31.7	75	88	2.50	0.47	0.22	0.69
3	1,220	36	28–39	739	100	8.9	3.2	28.2	75	87	3.00	0.64	0.19	0.83
9	1,200	30	37–41	598	105	6.9	4.1	28.0	84	87	4.00	0.58	0.23	0.81
13	1,200	31	35–43	620	107	10.8	2.5	27.5	83	83	3.00	0.44	0.15	0.59
14	1,200	32	30–37	674	97	12.5	2.4	30.0	75	83	3.17	0.63	0.24	0.87
17	1,200	30	29–31	518	79	14.1	1.6	23.0	86	83	3.00	0.52	0.29	0.81
18	1,280	63	21–33	940	88	17.7	2.4	41.8	63	83	4.18	0.63	0.22	0.85
19	1,180	40	34–42	688	108	13.2	2.4	32.1	79	83	3.50	0.44	0.21	0.65
22	2,160	33	45–49	645	124	14.4	1 9	28.6	85	83	3.75	0.53	0.27	0 80
25	1,800	62	32–50	477	128	10 3	2.3	23.8	66	94	3.50	0.59	0.27	0.86
29	1,180	30	24–32	572	79	11.6	2.4	28.0	73	92	3.20	0.57	0.15	0.72
30	1,060	28	35–40	566	98	8.6	3.0	25.8	87	85	4.00	0.62	0.19	0.81
31	1,880	46	38–50	433	123	9.9	1.9	19.3	57	83	3.00	0.62	0.30	0.92
Av.	1,342	39	32–40	627	101	11.7	2.5	28.3	76	86	3.37	0.56	0.22	0.78
Split-line arrangement; Diesel tractors														
5	1,320	35	53–60	720	142	14.7	2.3	33.6	91	88	3.85	0.57	0.15	0.72
11	1,180	44	30–35	682	89	9.5	3.4	32.5	81	90	3.50	0.43	0.10	0.53
12	1,400	69	28–49	1,143	120	18.8	2.7	51.0	75	83	3.33	0.39	0.08	0.47
20	1,280	34	29–44	685	111	10.0	3.2	32.0	73	83	3.00	0.56	0.12	0.68
28	1,140	36	26–41	737	100	11.1	3.1	34.5	73	87	4.00	0.46	0.12	0.58
34	1,200	58	32–49	1,150	121	20.3	2.5	51.6	74	84	3.70	0.36	0.07	0 43
Av.	1,253	46	33–46	853	114	14.1	1.9	39.2	78	86	3.56	0.46	0.12	0.56

Split-line arrangement; tractors and engines using other fuels†														
7	1,200	59	29–44	1,018	131	16.6	2.4	39.6	63	73	3.17	0.45	0.15	0.60
10	1,080	40	35–42	712	102	7.2	4.7	24.0	84	90	4.00	0.49	0.24	0.73
21	980	49	32–39	660	100	8.0	3.8	30.3	81	86	3.25	0.43	0.22	0.65
23	1,260	36	30–36	461	91	8.3	2.3	19.3	84	78	3.00	0.62	0.29	0.91
32	1,340	35	36–43	600	111	14.1	1.9	26.7	79	83	2.25	0.34	0.32	0.66
33	1,420	36	35–43	603	105	12.3	2.3	28.5	82	89	2.25	0.32	0.30	0.62
Av.	1,213	43	33–41	676	107	11.1	2.9	29.7	79	83	2.99	0.44	0.25	0.69
Single-line arrangement; tractors using stove oil														
2	1,020	32	28–45	453	122	4.7	2.6	12.1	62	50	3.00	0.50	0.21	0.71
4	1,340	35	16–39	508	117	6.4	3.5	22.5	48	80	2.25	0.40	0.21	0.61
8	920	30	22–35	384	86	9.2	1.6	14.5	69	71	3.00	0.83	0.24	1.07
24	1,320	34	24–45	498	114	7.8	2.7	21.3	60	80	3.00	0.56	0.20	0.76
26	980	46	19–39	548	116	8.2	2.6	21.3	48	73	2.50	0.47	0.23	0.70
35	760	25	26–39	415	103	5.6	3.2	17.7	67	80	3.00	0.68	0.26	0.94
Av.	1,057	34	23–40	468	109	7.0	2.7	18.2	59	72	2.79	0.57	0.23	0.80
Single-line arrangement; all others†														
6	880	44	23–37	438	89	8.8	1.8	15.6	67	67	3.00	0.77	0.31	1.08
15	1,420	36	26–59	525	157	16.4	1.1	18.7	52	67	3.00	0.96	0.18	1.14
16	1,280	33	23–44	392	111	7.6	0.9	6.5	59	75	3.00	1.38	0.45	1.83
27	700	34	25–32	358	86	2.8	2.9	8.0	70	83	3.25	0.81	0.27	1.08
36	1,400	35	27–50	450	133	6.4	1.6	10.5	56	87	2.73	0.50	0.20	0.70
37	1,120	28	36–48	401	122	5.7	1.9	10.7	75	86	2.63	0.49	0.20	0.69
Av.	1,133	35	27–45	427	116	8.0	1.7	11.7	63	78	2.92	0.82	0.27	1.09

* All portable pipe 4-inch O.D., except systems 5, 12, 31, and 34 where both 4-inch and 5-inch sizes were used; and system 10 where 3-inch and 4-inch sizes were used.
† Butane was used in systems 7, 36, and 37; gasoline in systems 6, 10, 16, 21, 27, 32, and 33; kerosene in system 23; and Diesel oil in system 15.

are summarized in table 2, and following text explains details of determining data in the columns.

Explanation of Table 2.—Column 4: The pressures at the sprinklers were determined with a calibrated pressure gauge attached to a special rubber fitting that was slipped over the main nozzle of the sprinkler. In doing this, the discharge of one sprinkler nozzle was shut off, momentarily increasing the pressure on the system. To obtain the correct pressure, therefore, it was necessary to determine this increase in pressure and subtract it from the gauge reading. The correction required, which varied with different systems, was usually between 0.5 and 1.5 pounds per square inch.

Column 5: The discharge of the pump was determined by summing up the discharge of the sprinklers, which was determined from the sprinkler calibrations and from the pressure measurements at the sprinklers.

Column 6: Total head includes the pressure at the pump plus the lift from the water surface in the ditch to the elevation of the sprinklers plus the velocity head at the pump discharge, all expressed in feet of head. The pressure at the pump was determined by adding the estimated friction loss in the pipe between the pump and the nearest sprinkler, to the pressure at that sprinkler.

Column 7: The area covered per day is determined by multiplying the area covered at each setting by the number of settings per day. The area covered at each setting was equal to the width of the field (approximate length of the line) times the distance the line is moved. The number of settings per day was either secured from the operators, or determined from the frequency of the moves. The figure given, therefore, represents the nominal area rather than the average area actually covered.

Column 8: The average depth of application in inches is determined by dividing the total application in acre-inches per day (column 9) by the area irrigated per day (column 7).

Column 9: The total application in acre-inches per day is determined from the discharge of the system and the estimated net operating time per day (column 11).

Column 10: The efficiency of the sprinkler system is the ratio of the total hydraulic energy at the sprinklers to the energy at the pump discharge, expressed as a percentage. The difference between the figure given and 100 per cent represents the loss of energy in the pipe by friction. Compare the average efficiency of the split-line arrangement and the single-line arrangement.

Column 11: The net operating time represents the approximate percentage of the total working day that the system was operating at full

capacity. For systems with a split line, where one line is operating while the other is being moved, the loss of time in moving was taken as the time required to move one line and the pumping plant.

Column 12: Where the average daily wage included board and room, an allowance was made for the value of the board and room in order to make the total wages comparable for all systems studied. In nearly all cases the daily wage was for 12 hours. These data are for 1935 and 1936, a period of relatively low wages.

Column 13: The average operating cost per acre-inch of water applied for labor is equal to the total daily wages paid divided by the total application in acre-inches per day (column 9).

Column 14: The cost of power per acre-inch of water applied was determined by dividing the total daily cost of fuel, lubricating oil, and miscellaneous expenses (as given by owners or operators) by the total output in acre-inches per day.

Column 15: The total operating cost is the sum of columns 13 and 14, no allowance being made for interest or depreciation on the equipment.

HYDRAULICS OF SPRINKLER SYSTEMS

Sprinkler systems are fairly complicated as compared with other irrigation systems. They are composed of many different kinds of mechanical and hydraulic equipment. They require careful planning in order to fit the fields on which they are to be used, and to be able to supply the water required for the various crops. Pipe sizes, nozzle sizes, pump sizes, and power requirements must be determined. Equipment must be selected and installed. The sprinkler system as a whole must be so proportioned that it will operate efficiently. The principal factors that enter into the cost of operation must be clearly understood. The planning of a sprinkler system is essentially an engineering function, and one that requires, especially, a knowledge of the hydraulic principles involved. The hydraulics of sprinkler systems is somewhat different than the usual problems in hydraulics that are encountered in engineering practice.[10]

The material covered in this and the following sections of the bulletin have been prepared primarily for engineers, and others engaged in the planning of sprinkler systems, and in the design, manufacture, and sale of sprinkler equipment. The information is presented in a somewhat

[10] Some phases of this subject have been discussed in previous papers; see: Christiansen, J. E. Irrigation by sprinkling. Agr. Engin. 18(12):533–38. Dec. 1937. Christiansen, J. E. Hydraulics of sprinkling systems for irrigation. Amer. Soc. Civ. Engin. Trans. 107:221–50. 1942. Christiansen, J. E. The uniformity of application of water by sprinkler systems. Agr. Engin. 22(3):89–92. March, 1941.

technical manner; mathematical symbols and formulas, that would otherwise be out of place, have been employed because they add to clearness and conciseness.

DISCHARGE FROM NOZZLES

The discharge from all types of nozzles and orifices can be expressed by the orifice formula, which is derived from Torricelli's theorem:

$$Q = CA\sqrt{2gH} \tag{1}$$

where Q is the discharge in cubic feet per second; C is the coefficient of discharge, which is approximately constant for a given nozzle or orifice; A is the area of the nozzle or orifices in square feet; g is the acceleration of gravity (32.2 feet per second per second); and H is the total head in feet, which includes the velocity head. This formula is not convenient to use, however, since the discharge from nozzles is commonly given in gallons per minute, nozzle dimensions are expressed in inches, and heads are expressed as pressures in pounds per square inch. Usually the velocity head in the riser is negligible in comparison with the pressure head and no correction for it need be made. Expressed in these units, equation 1 becomes

$$q = 38.00\,Ca\sqrt{P} \tag{2}$$

or

$$q = 29.85\,Cd^2\sqrt{P} \tag{3}$$

where q is the discharge in gallons per minute, a is the area of the nozzle in square inches, d is the diameter of the nozzle in inches, and P is the pressure in pounds per square inch. Table 3 gives the theoretical discharge ($C = 1.00$) of round nozzles from $\frac{1}{64}$ to $\frac{1}{2}$ inch in diameter. The actual discharge of a nozzle can be obtained by multiplying the discharge obtained from this table by the actual coefficient of discharge of the nozzle.

Coefficients of Discharge of Nozzles and Sprinklers.—The coefficient of discharge C of a nozzle is a ratio of the actual to the theoretical discharge. It is the product of two other coefficients: the coefficient of contraction and the coefficient of velocity. The coefficient of contraction is the ratio of the cross-sectional area of the jet, at the point of minimum area, to the area of the nozzle. For most sprinkler nozzles the coefficient of contraction is nearly 1.00. The coefficient of velocity for a sprinkler is the ratio of actual velocity at the nozzle to the theoretical velocity that would result if there were no friction losses in the sprinkler or nozzle. This coefficient is an important factor, since it indicates the energy loss due to friction and turbulence within the sprinkler. It is a measure of

TABLE 3

Theoretical Discharge of Sprinkler Nozzles*

Nozzle diameter, inches	Area, square inches	Discharge, in gallons per minute, for various pressures, in pounds per square inch																		
		10 lbs.	15 lbs.	20 lbs.	25 lbs.	30 lbs.	35 lbs.	40 lbs.	45 lbs.	50 lbs.	55 lbs.	60 lbs.	65 lbs.	70 lbs.	75 lbs.	80 lbs.	85 lbs.	90 lbs.	95 lbs.	100 lbs.
1/64........	0.00019	0.023	0.028	0.032	0.036	0.040	0.043	0.046	0.049	0.051	0.054	0.056	0.058	0.061	0.063	0.065	0.067	0.069	0.071	0.073
1/32........	0.00077	0.092	0.113	0.131	0.146	0.160	0.173	0.185	0.196	0.206	0.216	0.225	0.235	0.244	0.252	0.261	0.268	0.276	0.284	0.291
3/64........	0.00173	0.209	0.254	0.293	0.328	0.359	0.388	0.415	0.440	0.464	0.486	0.509	0.529	0.549	0.568	0.587	0.605	0.622	0.639	0.656
1/16........	0.00307	0.369	0.451	0.521	0.583	0.638	0.689	0.738	0.783	0.825	0.865	0.902	0.941	0.976	1.010	1.043	1.075	1.117	1.138	1.167
5/64........	0.00479	0.576	0.706	0.814	0.911	0.987	1.078	1.153	1.222	1.288	1.352	1.410	1.469	1.525	1.578	1.630	1.679	1.729	1.777	1.823
3/32........	0.00690	0.83	1.02	1.17	1.31	1.44	1.55	1.66	1.76	1.85	1.95	2.03	2.12	2.19	2.27	2.35	2.42	2.49	2.56	2.62
7/64........	0.00940	1.13	1.39	1.60	1.79	1.95	2.11	2.26	2.39	2.52	2.65	2.76	2.87	2.98	3.10	3.20	3.29	3.39	3.49	3.57
1/8........	0.01228	1.49	1.81	2.09	2.32	2.54	2.76	2.95	3.13	3.30	3.46	3.61	3.76	3.90	4.04	4.17	4.30	4.42	4.54	4.66
9/64........	0.01553	1.87	2.29	2.64	2.95	3.23	3.49	3.74	3.96	4.17	4.38	4.57	4.76	4.94	5.12	5.29	5.45	5.61	5.75	5.91
5/32........	0.01918	2.30	2.82	3.26	3.65	3.99	4.31	4.61	4.88	5.16	5.41	5.64	5.88	6.10	6.31	6.52	6.72	6.91	7.11	7.30
11/64........	0.02320	2.78	3.42	3.94	4.41	4.82	5.22	5.58	5.92	6.24	6.54	6.82	7.12	7.39	7.64	7.89	8.13	8.37	8.60	8.82
3/16........	0.02761	3.32	4.07	4.69	5.25	5.75	6.21	6.64	7.05	7.43	7.79	8.12	8.46	8.78	9.10	9.39	9.68	9.96	10.24	10.50
13/64........	0.03240	3.90	4.79	5.51	6.16	6.74	7.29	7.79	8.26	8.70	9.14	9.54	9.93	10.30	10.66	11.01	11.36	11.69	12.01	12.32
7/32........	0.03758	4.51	5.53	6.38	7.15	7.83	8.45	9.03	9.59	10.10	10.59	11.07	11.52	11.95	12.37	12.77	13.17	13.55	13.92	14.28
15/64........	0.04312	5.19	6.35	7.33	8.20	8.98	9.70	10.37	11.00	11.60	12.16	12.70	13.23	13.72	14.20	14.66	15.12	15.56	15.98	16.40
1/4........	0.04909	5.90	7.23	8.34	9.33	10.22	11.03	11.80	12.51	13.20	13.84	14.45	15.04	15.61	16.16	16.68	17.21	17.63	18.19	18.66
17/64........	0.05541	6.66	8.16	9.42	10.53	11.54	12.46	13.33	14.13	14.89	15.62	16.31	16.98	17.62	18.24	18.83	19.42	19.98	20.53	21.06
9/32........	0.06212	7.47	9.15	10.55	11.81	12.93	13.97	14.94	15.84	16.69	17.51	18.29	19.03	19.76	20.51	21.12	21.77	22.40	23.01	23.61
19/64........	0.06922	8.32	10.19	11.76	13.16	14.41	15.57	16.64	17.65	18.60	19.51	20.38	21.22	22.11	22.78	23.53	24.26	24.96	25.65	26.31
5/16........	0.07670	9.22	11.30	13.08	14.57	15.97	17.25	18.44	19.56	20.61	21.62	22.58	23.51	24.39	25.25	26.07	26.87	27.65	28.41	29.16
21/64........	0.08455	10.16	12.45	14.37	16.07	17.61	19.01	20.33	21.56	22.72	23.84	24.89	25.91	26.89	27.84	28.74	29.63	30.49	31.33	32.14
11/32........	0.09281	11.15	13.67	15.77	17.64	19.32	20.86	22.31	23.66	24.94	26.16	27.33	28.44	29.51	30.54	31.55	32.52	33.47	34.38	35.28
23/64........	0.10144	12.19	14.94	17.23	19.27	21.12	22.81	24.39	25.86	27.27	28.59	29.86	31.08	32.26	33.39	34.48	35.55	36.58	37.58	38.55
3/8........	0.11045	13.28	16.27	18.77	21.86	23.00	24.83	26.55	28.16	29.69	31.13	32.51	33.85	35.12	36.35	37.55	38.70	39.83	40.91	41.98
25/64........	0.11985	14.40	17.65	20.36	22.78	24.94	26.94	28.81	30.55	32.21	33.78	35.29	36.72	38.11	39.45	40.74	41.99	43.22	44.40	45.56
13/32........	0.12961	15.58	19.10	22.02	24.59	26.98	29.15	31.17	33.04	34.83	36.53	38.16	39.72	41.24	42.66	44.06	45.43	46.74	48.02	49.27
27/64........	0.13977	16.80	20.59	23.75	26.55	29.10	31.44	33.61	35.64	37.57	39.40	41.15	42.83	44.45	46.01	47.52	48.98	50.41	51.79	53.02
7/16........	0.15033	18.07	22.14	25.55	28.55	31.30	33.81	36.14	38.33	40.40	42.37	44.26	46.07	47.81	49.49	51.10	52.68	54.21	55.70	57.14
29/64........	0.16126	19.38	23.74	27.40	30.65	33.56	36.26	38.77	41.11	43.35	45.57	47.48	49.42	51.29	53.08	54.82	56.51	58.05	59.75	61.30
15/32........	0.17260	20.24	25.43	29.33	32.79	35.93	38.80	41.49	44.00	46.38	48.64	50.81	52.88	54.88	56.80	58.67	60.47	62.23	63.94	65.60
31/64........	0.18427	22.15	27.13	31.32	35.03	38.36	41.44	44.30	46.98	49.53	51.94	54.25	56.46	58.60	60.66	62.64	64.59	66.45	68.27	70.05
1/2........	0.19635	23.60	28.92	33.37	37.33	40.87	44.15	47.20	50.06	52.76	55.35	57.81	60.18	62.44	64.63	66.75	68.80	70.80	72.74	74.63

* Computed from the formula: $q = 29.85\, C\, d^2 \sqrt{P}$, where q is the discharge in gallons per minute, C is the coefficient of discharge of the nozzle (taken as 1.00 in these computations), d is the nozzle diameter in inches, and P is the total energy head expressed as pressure in pounds per square inch.

the sprinkler's efficiency in converting pressure to velocity—a high value indicating a small loss of energy. The coefficient of velocity for a sprinkler can be determined directly by dividing the pressure at the tip of the nozzle, determined with a Pitot gauge (fig. 19) by the pressure at the base of the sprinkler, corrected for velocity head and difference in elevation. The same pressure gauge should be used for both pressure measurements; if different gauges are used, small differences in the calibration of the gauges may cause an appreciable error in the coefficient.

The coefficients of discharge of well-designed sprinkler nozzles vary from about 0.95 to 0.98. Precise determinations of the coefficient of discharge are difficult; and unless precision instruments are used in the tests, determinations within 1 or 2 per cent are all that can be expected.

According to tests, coefficients of discharge for sprinklers with two or more nozzles vary from less than 0.80 for some sprinklers to about 0.98 for others, the coefficient for any sprinkler depends upon the construction of the sprinkler, the driving mechanism used, and the nozzle sizes. Sprinklers with internal driving mechanisms generally have the lowest coefficients; in some cases there is an appreciable loss of energy as the water passes through the sprinkler. The coefficient of discharge for the same sprinkler may vary considerably with different nozzle sizes. The larger the nozzles, the lower the coefficient, because of the higher velocity and the greater energy loss within the sprinkler. With a $\frac{3}{16}$-inch main nozzle, for example, a certain sprinkler has a coefficient of discharge of 0.97; with a $\frac{3}{8}$-inch main nozzle, a coefficient of only 0.88.

Discharge of Small Nozzles for Nozzle Lines.—The small nozzles used on nozzle lines are constructed differently from those used on sprinklers. They are more truly orifices in a thin wall. To minimize clogging, some of them are machined with an abrupt entrance, the base of the nozzle being slightly convex so that foreign matter will pass by without being trapped. The outer end is countersunk so that the length of the drilled hole is only about $\frac{1}{32}$ inch. The abrupt entrance causes a contraction of the jet, which passes through the nozzle without touching the sides of the opening. This results in a crystal-clear stream that travels a maximum distance. The length of the hole in some nozzles is sufficient so that the jet expands and fills the opening at the discharge end. Although the coefficient of discharge is higher, the result is a fuzzy jet that breaks up more rapidly and does not carry so far.

Tests on several of these nozzles gave coefficients of discharge between 0.8 and 0.9, the low values being due to the abrupt entrances. The nozzles tested had diameters varying from 0.034 to 0.045 inch, with discharges varying from a minimum of 0.10 gallon per minute at 13.5 pounds per square inch pressure, to a maximum of 0.34 gallon per minute at 42

pounds per square inch. Table 4, giving the discharge of small nozzles of this type at different pressures, is based on a coefficient of discharge of 0.85, the approximate average value of the nozzles tested.

Pressure Required for Sprinkler Operation.—For proper performance, all sprinklers require a certain minimum pressure. Some are designed for and operate best under fairly high pressures (more than 30 pounds per square inch), whereas others operate satisfactorily on pressures of 10 to 15 pounds. Pressure is needed to provide the velocity

TABLE 4

DISCHARGE OF SMALL NOZZLES FOR USE ON NOZZLE LINES*

Pressure, pounds per square inch	Discharge, in gallons per minute, for various nozzle diameters										
	0.030 inch	0.035 inch	0.040 inch	0.045 inch	0.050 inch	0.055 inch	0.060 inch	0.070 inch	0.080 inch	0.090 inch	0.100 inch
5	0.051	0.069	0.091	0.115	0.142	0.170	0.204	0.277	0.362	0.458	0.566
10	.072	.098	.128	.162	.200	.240	.289	.392	0.512	0.649	0.801
15	.088	.120	.157	.199	.245	.295	.353	.480	0.628	0.794	0.981
20	.102	.139	.181	.230	.283	.343	.408	.554	0.725	0.918	1.133
25	.114	.155	.203	.257	.317	.383	.456	.620	0.810	1.025	1.267
30	.125	.170	.222	.281	.347	.420	.500	.680	0.888	1.124	1.388
35	.135	.183	.240	.304	.374	.453	.540	.734	0.959	1.214	1.498
40	.144	.196	.256	.324	.400	.485	.577	.784	1.025	1.297	1.602
45	.153	.208	.272	.344	.425	.514	.612	.832	1.087	1.376	1.700
50	.161	.219	.286	.363	.448	.542	.645	.877	1.146	1.450	1.792
55	.169	.230	.300	.380	.470	.568	.676	.920	1.201	1.521	1.878
60	0.177	0.240	0.314	0.397	0.490	0.594	0.706	0.960	1.255	1.589	1.962

* Based on a coefficient of discharge, $C = 0.85$, an approximate average value for different nozzles tested.

which is required for two purposes: to secure distance of travel, or coverage; and to break up the water into small drops that can be properly distributed over the desired area. The first requirement can be satisfied only by a pressure adequate for this purpose. The second can be satisfied by other means, such as deflectors or shape of nozzle, but only at a sacrifice in the distance the water is thrown. Many sprinklers utilize both methods, having one round nozzle for distance, and a second nozzle with a deflector or slotted nozzle that breaks up the water into small drops that fall near the sprinkler.

Let us consider what happens as the pressure is gradually increased on a single round sprinkler nozzle. With very low pressure the water issues in a solid stream, and all of it strikes the ground about the same distance from the sprinkler. If the sprinkler rotates, only a narrow ring receives water. With increase in pressure, the water becomes broken up into drops and covers a larger and wider ring. Upon examining the drops that strike the ground, we find that the largest are carried to the

outside edge of the area covered, while the smallest fall near the sprinkler. With further increase in pressure the width of the ring becomes equal to the radius, and the entire area receives water. As the pressure continues to increase, more and more of the water falls near the sprinkler, and the average size of the drops becomes smaller and smaller. The effective coverage of the sprinkler, which governs the permissible spacing of sprinklers, will increase with pressure up to a certain point, and will then decrease with further increase in pressure because of the larger percentage of water falling near the sprinkler. The larger the nozzle, the higher the pressure will be at maximum effective coverage.

The minimum pressure required for most sprinkler nozzles varies from about 15 to 40 pounds per square inch. The larger the nozzles and the greater the capacity of the sprinkler, the higher the pressure required for satisfactory distribution. Most field and orchard sprinklers, except some under-tree sprinklers, operate under pressures between 20 and 60 pounds per square inch. Some very large sprinklers built for special purposes require pressures of 100 to 150 pounds and cover diameters up to 300 feet.

Special low-pressure sprinklers are available. Some of the small under-tree orchard types operate on pressures as low as 5 pounds per square inch and will cover adequately the area between adjacent trees.

The pressures mentioned above are those required at the sprinkler. When pressures are determined at any point other than the sprinkler, they must be corrected both for frictional losses and for differences in elevation to obtain the actual pressure under which the sprinkler is operating. Sometimes a user assumes that his system is operating under the pressure indicated by a gauge at the pump or source of supply, whereas some of the sprinklers may actually be working under a much lower pressure.

FLOW OF WATER IN PIPE

The flow of water through a pipe is always accompanied by a loss of head due to friction. Additional loss of head is also caused by sharp bends, sudden enlargements or contractions in the pipe, or other obstructions. Figure 23 illustrates the effect of friction. The hydraulic grade line is an imaginary line joining the elevation at which water would stand in open columns connected with the pipe line. The height of the hydraulic grade line above the pipe represents the head or pressure at any point on the line. The friction loss is represented by a decrease in the elevation to which water will rise in the columns, or by the slope of the hydraulic grade line. The friction loss does not always produce a decrease in pressure in the pipe line. If the slope of the pipe line is greater than the slope of the hydraulic grade line, there will be an

increase in pressure, that is (as illustrated in fig. 23), the total head or pressure H_B, above the pipe line at B, may be greater than the head H_A at A. A measurement of the difference in pressure at two points on a pipe line is, therefore, not a measure of the friction loss unless the line is level, or unless corrections are made for differences in elevation.

Formulas for Friction Loss in Pipe Lines.—Friction losses in pipe lines depend principally upon the roughness of the inside of the pipe, the size of the pipe, and the velocity of the water. Many formulas have been proposed to express the relation between these principal factors.

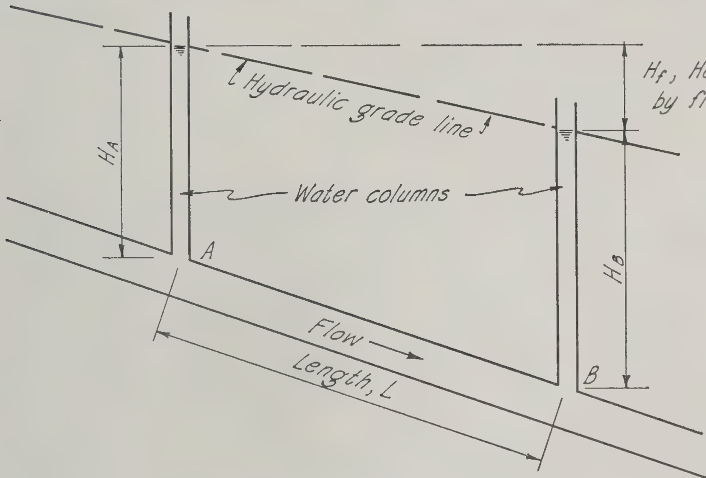

Fig. 23.—Diagram illustrating friction loss in pipe lines.
See the text for explanation.

The formulas are based upon numerous tests on pipes of different kinds and sizes. The three formulas most commonly used as a basis for tables and diagrams for friction losses in pipe of the kind used for sprinkler systems are Weisbach's, Williams and Hazen's, and Scobey's. When written in the same form, these formulas are as follows:

Weisbach's:[11]

$$H_f = \frac{fLV^2}{2gD}. \tag{4}$$

Williams and Hazen's:[12]

$$H_f = \frac{3.022\,LV^{1.852}}{C^{1.852}\,D^{1.167}}. \tag{5}$$

[11] This equation, sometimes called the Darcy formula, is mentioned in any standard textbook on hydraulics.

[12] This equation is commonly written $V = 0.001^{-0.04}\,C\,R^{0.63}\,S^{0.54}$, or $V = 1.318\,C\,R^{0.63}\,S^{0.54}$. See: Williams, Gardner S., and Allen Hazen. Hydraulic tables. 115 p. John Wiley & Sons. New York, N. Y.

TABLE 5

FRICTION LOSS IN STANDARD WROUGHT-IRON OR STEEL PIPE FOR $C = 100$*

Flow, gallons per minute	Friction loss, in feet of head, for each 100 feet of pipe in the following nominal pipe sizes †										
	¾ inch	1 inch	1¼ inches	1½ inches	2 inches	2½ inches	3 inches	3½ inches	4 inches	5 inches	6 inches
3	4.1	1.3	0.33	0.16	.....	.....	.....	.....	.....	.....	.....
4	6.9	2.1	0.56	0.26	0.08	.....	.....	.....	.....	.....	.....
5	10.5	3.2	0.85	0.40	0.12	.....	.....	.....	.....	.....	.....
6	14.7	4.5	1.19	0.56	0.17	.....	.....	.....	.....	.....	.....
8	25.0	7.7	2.03	0.96	0.28	0.12	.....	.....	.....	.....	.....
10	37.8	11.6	3.06	1.44	0.43	0.18	.....	.....	.....	.....	.....
12	52.9	16.3	4.29	2.03	0.60	0.25	0.09	.....	.....	.....	.....
14	70.4	21.7	5.71	2.69	0.80	0.34	0.12	.....	.....	.....	.....
16	90.2	27.8	7.32	3.45	1.02	0.43	0.15	0.07	.....	.....	.....
18	.....	34.6	9.10	4.29	1.27	0.53	0.19	0.09	.....	.....	.....
20	.....	42.1	11.1	5.21	1.55	0.65	0.23	0.11	.....	.....	.....
25	.....	63.6	16.7	7.89	2.34	0.98	0.34	0.17	0.09	.....	.....
30	.....	89.2	23.4	11.1	3.28	1.38	0.48	0.24	0.13	.....	.....
35	.....	.....	31.3	14.7	4.36	1.83	0.64	0.31	0.17	.....	.....
40	.....	.....	39.9	18.8	5.58	2.35	0.82	0.40	0.22	0.07	.....
45	.....	.....	49.6	23.4	6.94	2.92	1.01	0.50	0.27	0.09	.....
50	.....	.....	60.4	28.5	8.44	3.55	1.23	0.61	0.33	0.11	.....
55	.....	.....	72.0	34.0	10.1	4.24	1.47	0.72	0.39	0.13	.....
60	.....	.....	84.5	39.9	11.8	4.97	1.73	0.85	0.46	0.15	.....
70	.....	.....	.....	53.1	15.7	6.62	2.30	1.13	0.61	0.20	0.08
80	.....	.....	.....	68.0	20.2	8.48	2.94	1.45	0.78	0.26	0.11
90	.....	.....	.....	84.5	25.1	10.6	3.66	1.80	0.97	0.32	0.13
100	.....	.....	.....	.....	30.5	12.8	4.44	2.19	1.18	0.39	0.16
120	.....	.....	.....	.....	42.7	18.0	6.23	3.07	1.66	0.55	0.23
140	.....	.....	.....	.....	56.8	23.9	8.30	4.09	2.21	0.73	0.30
160	.....	.....	.....	.....	72.9	30.6	11.3	5.24	2.83	0.94	0.38
180	.....	.....	.....	.....	90.5	38.0	13.2	6.51	3.54	1.17	0.48
200	.....	.....	.....	.....	.....	46.3	16.1	7.92	4.28	1.42	0.58
250	.....	.....	.....	.....	.....	70.0	24.3	12.0	6.47	2.15	0.88
300	.....	.....	.....	.....	.....	98.0	34.0	16.7	9.06	3.01	1.23
350	.....	.....	.....	.....	.....	.....	45.3	22.3	12.1	4.01	1.64
400	.....	.....	.....	.....	.....	.....	58.0	28.6	15.4	5.13	2.10
450	.....	.....	.....	.....	.....	.....	72.0	35.5	19.2	6.38	2.61
500	.....	.....	.....	.....	.....	.....	87.6	43.4	23.3	7.76	3.17
550	.....	.....	.....	.....	.....	.....	.....	51.6	27.9	9.27	3.79
600	.....	.....	.....	.....	.....	.....	.....	60.5	32.7	10.9	4.45
700	.....	.....	.....	.....	.....	.....	.....	80.5	43.5	14.5	5.92
800	.....	.....	.....	.....	.....	.....	.....	.....	55.8	18.5	7.58
900	.....	.....	.....	.....	.....	.....	.....	.....	69.3	23.0	9.31
1,000	.....	.....	.....	.....	.....	.....	.....	.....	84.2	28.0	11.44

* Computed from Williams and Hazen's formula.

† To convert head in feet to pressure in pounds per square inch, divide by 2.31.

TABLE 6

FRICTION LOSS IN STANDARD WROUGHT-IRON OR STEEL PIPE FOR $C = 120$*

Flow, gallons per minute	Friction loss, in feet of head, for each 100 feet of pipe in the following nominal pipe sizes †										
	¾ inch	1 inch	1¼ inches	1½ inches	2 inches	2½ inches	3 inches	3½ inches	4 inches	5 inches	6 inches
3	2.9	0.9	0.23	0.11	.....	.....	.....	.....	.....	.....	.....
4	4.9	1.6	0.40	0.19	0.06	.....	.....	.....	.....	.....	.....
5	7.5	2.4	0.61	0.29	0.08	.....	.....	.....	.....	.....	.....
6	10.5	3.3	0.85	0.40	0.12	.....	.....	.....	.....	.....	.....
8	17.8	5.6	1.45	0.68	0.20	0.08	.....	.....	.....	.....	.....
10	27.0	8.5	2.19	1.03	0.31	0.13	.....	.....	.....	.....	.....
12	37.7	11.9	3.06	1.45	0.43	0.18	0.06	.....	.....	.....	.....
14	50.2	15.9	4.07	1.92	0.57	0.24	0.08	.....	.....	.....	.....
16	64.3	20.3	5.22	2.46	0.73	0.31	0.11	0.05	.....	.....	.....
18	80.0	25.3	6.49	3.06	0.91	0.38	0.13	0.07	.....	.....	.....
20	97.3	30.7	7.90	3.72	1.10	0.46	0.16	0.08	.....	.....	.....
25	.....	46.4	11.9	5.64	1.67	0.70	0.24	0.12	0.07	.....	.....
30	.....	65.1	16.7	7.90	2.34	0.98	0.34	0.17	0.09	.....	.....
35	.....	86.6	22.2	10.5	3.11	1.31	0.45	0.22	0.12	.....	.....
40	.....	.....	28.5	13.5	3.98	1.67	0.58	0.29	0.16	0.05	.....
45	.....	.....	35.4	16.7	4.95	2.08	0.72	0.36	0.20	0.06	.....
50	.....	.....	43.1	20.3	6.02	2.53	0.88	0.43	0.24	0.08	.....
55	.....	.....	51.4	24.3	7.18	3.02	1.04	0.52	0.29	0.09	.....
60	.....	.....	60.4	28.5	8.43	3.55	1.23	0.61	0.34	0.11	.....
70	.....	.....	80.4	37.9	11.2	4.72	1.63	0.81	0.45	0.15	0.06
80	.....	.....	.....	48.5	14.4	6.04	2.09	1.03	0.57	0.19	0.08
90	.....	.....	.....	60.4	17.9	7.52	2.60	1.29	0.71	0.23	0.09
100	.....	.....	.....	73.4	21.7	9.14	3.16	1.56	0.86	0.28	0.11
120	.....	.....	.....	.....	30.5	12.8	4.43	2.19	1.21	0.39	0.16
140	.....	.....	.....	.....	40.5	17.0	5.89	2.92	1.61	0.52	0.21
160	.....	.....	.....	.....	52.0	21.8	7.55	3.74	2.07	0.67	0.27
180	.....	.....	.....	.....	64.5	27.1	9.38	4.64	2.57	0.83	0.34
200	.....	.....	.....	.....	78.5	33.0	11.4	5.65	3.12	1.01	0.41
250	.....	.....	.....	.....	.....	50.0	17.2	8.54	4.72	1.53	0.63
300	.....	.....	.....	.....	.....	70.0	24.2	12.0	6.61	2.15	0.88
350	.....	.....	.....	.....	.....	93.0	32.1	15.9	8.80	2.86	1.17
400	.....	.....	.....	.....	.....	.....	41.2	20.4	11.3	3.66	1.50
450	.....	.....	.....	.....	.....	.....	51.2	25.3	14.0	4.56	1.86
500	.....	.....	.....	.....	.....	.....	62.3	30.8	17.0	5.54	2.26
550	.....	.....	.....	.....	.....	.....	74.4	36.8	20.3	6.11	2.70
600	.....	.....	.....	.....	.....	.....	87.3	43.2	23.9	7.75	3.17
700	.....	.....	.....	.....	.....	.....	.....	57.4	31.8	10.3	4.21
800	.....	.....	.....	.....	.....	.....	.....	73.6	40.7	13.2	5.40
900	.....	.....	.....	.....	.....	.....	.....	91.4	50.6	16.4	6.71
1,000	.....	.....	.....	.....	.....	.....	.....	.....	61.5	20.0	8.16

* Computed from Williams and Hazen's formula.
† To convert head in feet to pressure in pounds per square inch, divide by 2.31.

Scobey's:[13]

$$H_f = \frac{K_s L V^{1.9}}{1{,}000\, D^{1.1}} \tag{6}$$

where H_f is the friction loss in length of pipe, L, in feet; V is the mean velocity in feet per second; D is the diameter of pipe in feet; g is the acceleration of gravity, about 32.2 feet per second per second; f is the Weisbach friction factor, which varies with smoothness, size of pipe, and velocity, values ranging from about 0.015 for large smooth pipes to about 0.050 for very rough pipes; C is Williams and Hazen's coefficient, which varies with smoothness of pipe, values ranging from about 70 for rough pipes to about 140 for very smooth pipe; and K_s is Scobey's coefficient of retardation, which varies with smoothness of pipe, values ranging from about 0.30 for smooth pipe to 1.0 or higher for very rough pipe.

Friction Loss in Standard Pipe.—Table 5 gives the friction loss in standard iron pipe as computed from Williams and Hazen's formula. The losses are expressed in feet per 100 feet of pipe. This table is based on a coefficient, $C \doteq 100$, corresponding to iron pipe that has been in use for ten to twenty years. This table is commonly employed for design purposes. Table 6 is based on Williams and Hazen's formula with $C = 120$. This table is believed safe for use with galvanized pipe under ordinary conditions. Coefficients for new pipe normally range from 120 to 130; for old, badly corroded, tuberculated pipe they may be as low as 50 or 60. These very low values are due largely to a reduction in the cross-section area of the pipe, since the coefficients are computed on the full pipe area. The actual inside diameters and cross-section areas of standard weight pipe are as follows:

Pipe size, inches	Inside diameter, inches	Area, square inches
½	0.622	0.30
¾	0.824	0.53
1	1.049	0.86
1¼	1.380	1.49
1½	1.610	2.04
2	2.067	3.35
2½	2.469	4.78
3	3.068	7.38
3½	3.548	9.88
4	4.026	12.72
5	5.047	20.00
6	6.065	28.90

[13] Scobey, Fred C. The flow of water in riveted steel and analogous pipes. U. S. Dept. Agr. Tech. Bul. **150**:1–136. 1930.

The friction loss in pipe corresponding to other values of C can be determined by multiplying the head loss, as given in table 5 for $C = 100$, by the following factors:

C	Factor	C	Factor
40	5.40	90	1.22
50	3.61	110	0.838
60	2.58	120	0.713
70	1.94	130	0.615
80	1.51	140	0.536

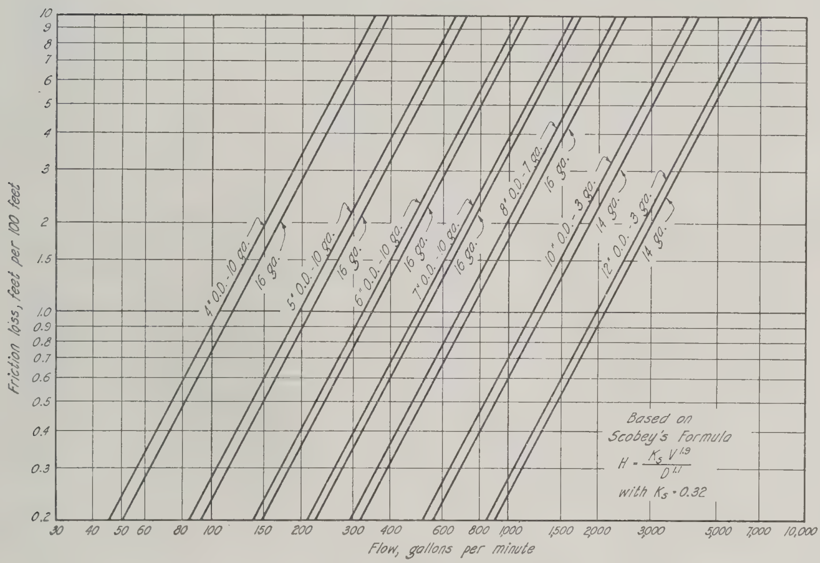

Fig. 24.—Friction loss in welded steel O.D. pipe. The double lines indicate differences in friction loss between pipes of the lightest and heaviest wall as commonly made.

Friction Loss in Welded Steel Pipe.—Figure 24 shows the friction loss in welded steel pipe of the type commonly used for main supply lines for portable sprinkler systems. This graph is based on Scobey's formula, with the coefficient $K_s = 0.32$, which corresponds to new pipe in good condition. Since welded steel pipe is relatively thin, it is usually protected against corrosion by galvanizing or with an asphalt or tar coating, with or without a protective wrapping. The effectiveness of these coatings in maintaining a high carrying capacity depends entirely upon the material used and the corrosiveness of the water. In designing stationary pipe layouts for sprinkler systems, one may well add a

certain amount to the required flow, to serve as a factor of safety; an allowance of 10 to 20 per cent is usual.

Friction Loss in Copper Tubing.—Copper tubing (also called copper pipe) is available in both soft and hard temper. It is made in four stand-

TABLE 7

FRICTION LOSS IN TYPE M COPPER TUBING*

Flow, gallons per minute	Friction loss, in feet of head, for each 100 feet of tubing in the following nominal sizes†					
	½ inch	¾ inch	1 inch	1¼ inches	1½ inches	2 inches
1	1.7	....	....	.....	.....	.....
2	6.1	1.1	....	.....	.....	.....
3	14.0	2.4	0.7	.....	.....	.....
4	22.2	4.0	1.2	0.42	.....	.....
5	34.0	6.1	1.8	0.63	0.28	.....
6	47.0	8.5	2.4	0.88	0.39	0.10
8	80.0	14.4	4.1	1.51	0.66	0.17
10	....	21.9	6.3	2.28	1.01	0.27
12	....	30.5	8.8	3.18	1.42	0.37
14	....	40.8	11.8	4.23	1.87	0.49
16	....	52.1	15.0	5.43	2.40	0.63
18	....	64.8	18.7	6.75	2.99	0.78
20	....	78.8	22.7	8.22	3.63	0.95
25	....	....	34.3	12.4	5.51	1.44
30	....	....	48.2	17.4	7.71	2.01
35	....	....	64.0	23.1	10.2	2.67
40	....	....	....	29.6	13.2	3.42
45	....	....	....	36.8	16.3	4.26
50	....	....	....	44.8	19.8	5.18
60	....	....	....	62.9	27.8	7.25
70	....	....	....	.....	37.0	9.64
80	....	....	....	.....	47.3	12.32
90	....	....	....	.....	59.0	15.36
100	....	....	....	.....	71.6	18.68

* From Williams and Hazen's formula, $C = 140$.
† Actual inside diameters are given in table 8.

ardized types O, M, L, and K, classified according to wall thickness. The outside diameters of all types are ⅛ inch greater than the nominal sizes. One-inch tubing is, for example, 1⅛ inches O.D., and varies from 1.055 inches I.D. for type M to 0.995 inch for type K. The lightest weight, type O, is available only in sizes above 3 inches.

Since the inside diameter of copper tubing is usually less than the inside diameter of iron pipe of the same nominal size, the friction loss is sometimes greater than for iron pipe. This is particularly true of the

heavier-walled tubing, types L and K, and of ½-inch and 1¼-inch sizes. For this reason friction loss tables for iron pipe are not suitable for estimating the carrying capacity of copper tubing.

Tests to determine friction losses in pipe of various kinds generally indicate a lower value for the exponent of V for smooth pipes, than for rough pipes. Dawson's[14] formula for flow of water in copper pipe can be written:

$$H_f = \frac{0.000315\, LV^{1.75}}{D^{1.25}}. \tag{7}$$

This equation corresponds approximately to Williams and Hazen's formula with $C = 140$. Tests by A. F. Pillsbury[15] on ¾-inch copper tubing indicate slightly lower losses than given by Dawson's formula, but they verify this exponent of V. Table 7, computed from Williams and Hazen's formula, with $C = 140$, gives the friction loss in type M copper tubing, sizes 0.5 to 2 inches. Table 8 compares the inside diameters

TABLE 8

COMPARISON OF INSIDE DIAMETERS AND FRICTION LOSSES IN COPPER TUBING, TYPES M, L, AND K*

Nominal size, inches	Type M (light)		Type L (medium)		Type K (heavy)	
	Inside diameter, inches	Friction factor	Inside diameter, inches	Friction factor	Inside diameter, inches	Friction factor
½	0.569	1.00	0.545	1.23	0.527	1.52
¾	0.811	1.00	0.785	1.17	0.745	1.52
1	1.055	1.00	1.025	1.15	0.995	1.33
1¼	1.291	1.00	1.265	1.10	1.245	1.19
1½	1.527	1.00	1.505	1.08	1.481	1.16
2	2.009	1.00	1.985	1.06	1.951	1.15

* The friction loss in copper tubing, types *L* and *K*, can be found by multiplying the loss given in table 7 by the friction factor given in this table.

and friction loss in types M, L, and K. To determine the friction loss in types L or K it is necessary to multiply the friction loss given in table 7 by the proper friction factor from table 8.

Friction Loss in Garden Hose and Hydrants.—Garden hose in ¾- and 1-inch sizes is used to a large extent in connection with sprinkler systems for orchards and also for lawns. In general, friction loss through hose of this type is appreciably higher than for iron pipe and probably varies with different makes of hose. According to recent tests at Davis,

[14] Dawson, F. M., and J. S. Bowman. Interior water supply piping for residential buildings. Wisconsin Engin. Exp. Sta. Bul. 77:1–54. 1933.

[15] Unpublished data.

the friction loss varies with the pressure, the loss becoming less as the hose swells under pressure. Table 9 gives the friction loss in 100 feet of hose and the loss through garden valves of the type generally used as hydrants for small sprinkler systems.

FLOW OF WATER IN PIPES WITH MULTIPLE OUTLETS

The friction loss in pipe lines with sprinklers or nozzles spaced equidistant along the line can be calculated in a step-by-step process, computing the loss for each length between adjacent sprinklers for which the

TABLE 9

APPROXIMATE FRICTION LOSS IN GARDEN HOSE AND GARDEN HYDRANTS*

Flow, gallons per minute	Friction loss, in pounds per square inch, for:†			
	100 feet of ¾-inch hose	100 feet of 1-inch hose	¾-inch garden hydrant	1-inch garden hydrant
5	6.8	1.6	0.3	0.1
6	9.6	2.0	0.4	0.2
7	12.8	2.8	0.6	0.2
8	16.0	3.6	0.8	0.3
9	20.0	4.4	1.0	0.4
10	24.4	5.6	1.2	0.5
12	34.0	8.0	1.7	0.7
14	45.2	10.4	2.4	0.9
16	58.0	13.2	3.1	1.2
18	72.0	16.4	3.9	1.5
20	88.0	20.0	4.8	1.9
22	....	24.0	5.8	2.3
24	....	28.0	6.9	2.7
26	....	32.4	8.0	3.2
28	....	37.2	9.2	3.7
30	....	42.0	10.6	4.3

* Friction losses in hose and valves vary widely with different makes of equipment. These values, based on tests at Davis, should be used only as a guide in determining the size required.

† To convert pressure in pounds per square inch to head in feet, multiply by 2.31.

flow is constant. Such calculations are tedious, especially for long lines. Starting at the distal end of the line with an assumed pressure and sprinkler discharge, one must work back toward the source to determine the required pressure and the total flow for the line. By making certain approximations, however, one can obtain a simple and fairly accurate solution.

Derivation of Equations for Calculating Friction Losses.—If the line is level, the pressure will be a minimum at the distal end of the line, and will increase gradually toward the source. The discharge of the end sprinkler will be a minimum, and, as we proceed toward the pump, each sprinkler in turn will discharge slightly more water because of the increase in pressure. The variation in the discharge of the sprinklers is

ordinarily not great, and to simplify the calculation of the friction loss, we will assume that the discharge of each sprinkler on the line is equal to the average discharge of all of the sprinklers, that is

$$q_1 = q_2 = q_3 = q_a = \frac{Q}{N} \tag{8}$$

when q_1, q_2, and q_3 are the discharges of the first, second, and third sprinklers respectively, and q_a is the average discharge of all the sprinklers which is equal to the total discharge Q divided by the number of sprinklers, N. A relation between the friction loss in lines with multiple outlets and ordinary pipe lines, where all of the water is carried to the end of the line, can then be derived from a general equation for flow of water in pipe lines. Writing equations 4, 5, and 6 in a generalized form,

$$H_f = \frac{K_1 L V^m}{D^n} \tag{9}$$

but

$$V = \frac{Q}{A} = \frac{Q}{\frac{\pi D^2}{4}} = \frac{K_2 Q}{D^2}$$

and

$$V^m = \frac{K_2{}^m Q^m}{D^{2m}}$$

Making this substitution for V^m, and combining K_1 and $K_2{}^m$, we get

$$H_f = \frac{KLQ^m}{D^{2m+n}}. \tag{10}$$

For pipes with multiple outlets, the total friction loss is equal to the sum of the losses between adjacent outlets. Letting q_a equal the discharge at each outlet, and S equal the spacing between outlets, the friction loss between the last two outlets at the distal end of the line becomes

$$h_1 = \frac{KSq_a{}^m}{D^{2m+n}} \tag{11}$$

and the loss between the next two outlets is

$$h_2 = \frac{KS(2q_a)^m}{D^{2m+n}} = \frac{KSq_a{}^m 2^m}{D^{2m+n}} \tag{12}$$

and, similarly

$$h_N = \frac{KSq_a{}^m N^m}{D^{2m+n}}. \tag{13}$$

The total friction loss for any number of spaces N, between adjacent outlets, becomes

$$H_f = \Sigma(h_1 + h_2 + \cdots + h_N) = KSq_a^m \Sigma (1^m + 2^m + 3^m + \cdots + N^m). \quad (14)$$

Substituting $\frac{L}{N}$ for S, $\frac{Q}{N}$ for q_a, and ΣN^m for $\Sigma(1^m + 2^m + 3^m + \cdots + N^m)$ we have

$$H_f = \frac{K}{D^{2m+n}}\left(\frac{L}{N}\right)\left(\frac{Q^m}{N^m}\right)\Sigma N^m = \frac{\Sigma N^m}{N^{m+1}}\left(\frac{KLQ^m}{D^{2m+n}}\right) = F\left(\frac{KLQ^m}{D^{2m+n}}\right). \quad (14)$$

Comparing this equation with equation 10 we see that the friction loss in a pipe with multiple outlets can be determined by first estimating the

TABLE 10

VALUES OF THE FACTOR F* BY WHICH THE FRICTION LOSS IN PIPE MUST BE MULTIPLIED TO OBTAIN THE ACTUAL LOSS IN A LINE WITH MULTIPLE OUTLETS

Number of outlets	$m = 1.85$	$m = 1.90$	$m = 2.00$
1	1.0	1.0	1.0
2	0.639	0.634	0.625
3	0.535	0.528	0.518
4	0.486	0.480	0.469
5	0.457	0.451	0.440
6	0.435	0.433	0.421
7	0.425	0.419	0.408
8	0.415	0.410	0.398
9	0.409	0.402	0.391
10	0.402	0.396	0.385
11	0.397	0.392	0.380
12	0.394	0.388	0.376
13	0.391	0.384	0.373
14	0.387	0.381	0.370
15	0.384	0.379	0.367
16	0.382	0.377	0.365
17	0.380	0.375	0.363
18	0.379	0.373	0.361
19	0.377	0.372	0.360
20	0.376	0.370	0.359
22	0.374	0.368	0 357
24	0.372	0.366	0.355
26	0.370	0.364	0.353
28	0.369	0.363	0.351
30	0.368	0.362	0.350
35	0.365	0.359	0.347
40	0.364	0.357	0.345
50	0.361	0.355	0.343
100	0.356	0.350	0.338
∞	0.351	0.345	0.333

* $F = \frac{\Sigma N^m}{N^{m+1}}$, as given in equation 14.

friction loss in the line, assuming that all the water is carried to the end of the line, and then multiplying this loss by a factor, F, that depends on the number of outlets on the line and the value of m used in the friction loss formula. Any suitable formula, table or graph may be used, therefore, for estimating the friction loss in lines with multiple outlets. Values of the factor F, have been calculated, and are given in table 10 for $m = 1.85$, 1.9, and 2.0. Values of this factor for any other value of m can be readily computed from the approximate expression[16]

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2}. \tag{15}$$

According to tests on sprinkler pipe with sprinklers uniformly spaced along the line the friction factor K is lower, and the exponent m is slightly higher, than for ordinary pipe flow, because of the partial recovery of velocity head at each outlet. For many problems, a value of $m = 2$ can be used.

Friction Loss in Sprinkler Lines.—Most portable sprinkler pipe is made from lightweight O.D. tubing. A special graph, figure 25, shows the friction loss in 16- and 18-gauge sprinkler pipe in sizes 1 to 6 inches O.D. This graph is based on Scobey's formula, with coefficient K_s as given. According to tests on such pipe, higher values of K_s may be expected of the smaller sizes, and the values are influenced by the type of coupling. The values given are believed conservative; most sprinkler pipe will have less friction loss than is shown by the graph. Some of the tests indicated that the pressure drop for each section of pipe between adjacent sprinklers is approximately proportional to the square of the velocity (V^2) in that section of pipe, as given in Weisbach's formula, instead of some lower power of V as given in Williams and Hazen's or Scobey's formulas. The reason for this is, that the velocity head is partially recovered at each sprinkler outlet where the mean velocity in the pipe is suddenly reduced. For estimating the friction loss in a line of sprinkler pipe with sprinklers, it makes little difference whether Weisbach's or Scobey's formula is used; but for estimating the loss in a line without sprinklers, Scobey's formula is preferable, unless different values of f are selected for different velocities. Where calculations from a formula are required, Weisbach's formula will be found easier to use. For sprinkler pipe, the following values of f are suggested:[17]

[16] This expression is exact for $m = 1$, and $m = 2$, and very nearly correct for $m = 3$ and intermediate values. Where N is greater than 10, the last term in the expression is negligible and can be omitted.

[17] Based upon field and laboratory tests on several makes of sprinkler pipe, and supplemented by published data, principally from Pigott, R. J. S. The flow of fluids in closed conduits. Mech. Engin. 55(8):497–501, 515. August, 1933.

1-inch, 0.028; 1½-inch, 0.025; 2-inch, 0.023; 2½-inch, 0.022; 3-inch, 0.021; 4-inch, 0.020; 5-inch, 0.019; and 6-inch, 0.018.

To simplify further the problem of determining friction losses in sprinkler pipe, a logarithmic chart, figure 26, has been prepared. This combines data given in figure 25 and table 10. Although based on a sprinkler spacing of 20 feet, it can be used for any spacing if the

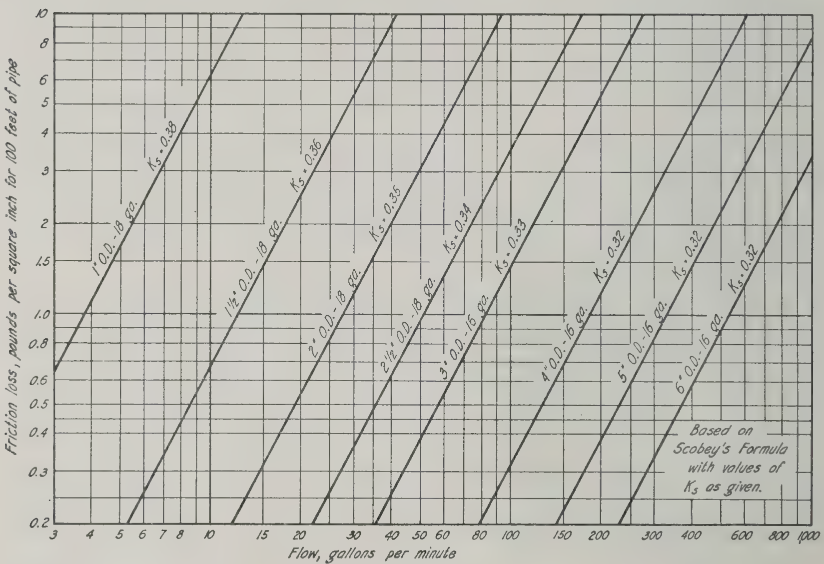

Fig. 25.—Friction loss in portable sprinkler pipe. For mains and supply lines, where all of the water passes through all of the pipe, this diagram is sufficient. For lines equipped with sprinklers, it must be used in conjunction with table 10.

friction loss obtained from the diagram be multiplied by the ratio: $\frac{\text{actual spacing-feet}}{20}$. To determine, for instance, the friction loss in a 600-foot line of 3-inch pipe with sprinklers discharging 11 gallons per minute, spaced 40 feet apart:

1. There will be $\frac{600}{40} = 15$ sprinklers.

2. Enter left side of diagram for $q = 11$; follow to right to intersection with 3-inch pipe.

3. Drop vertically down to a point half way between the lines for 14 and 16 sprinklers.

4. Follow to the right margin, and read friction loss of 4.1 pounds per square inch.

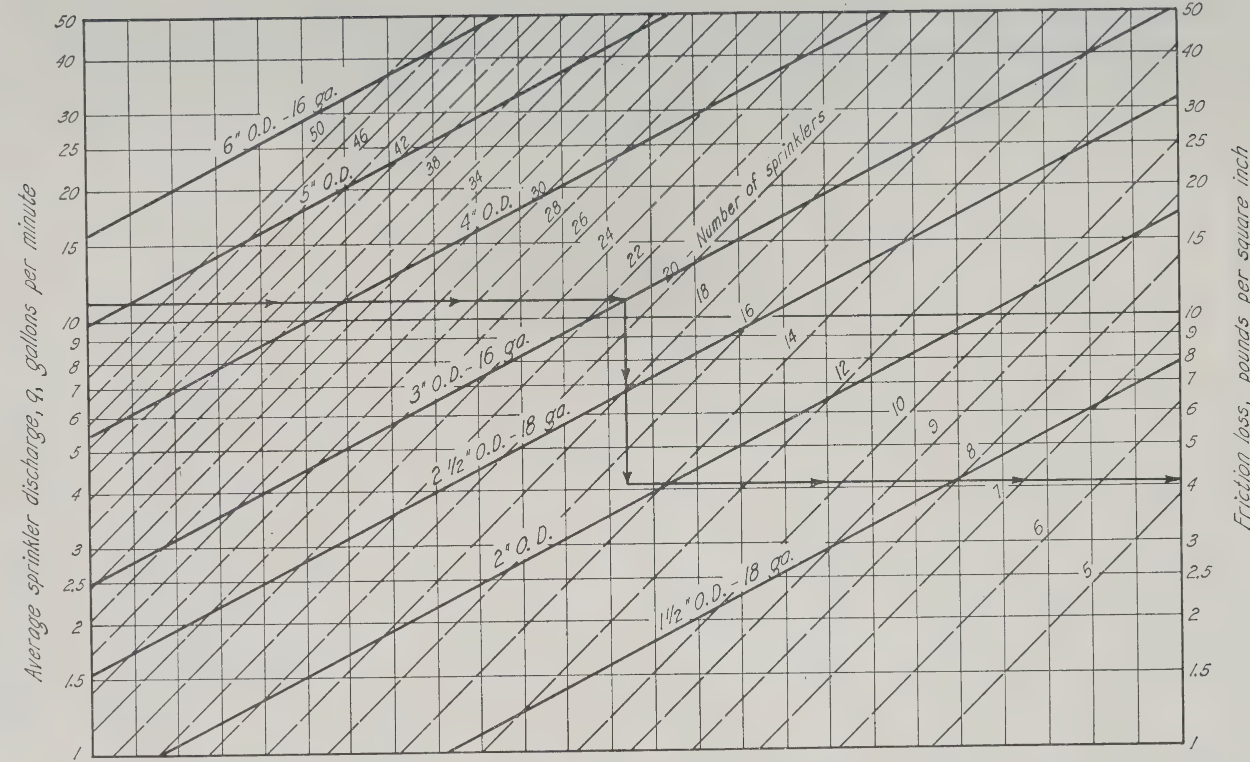

Fig. 26.—Logarithmic chart for determining friction loss along sprinkler lines with sprinklers spaced 20 feet apart. For any other sprinkler spacing, multiply friction loss obtained from this diagram by $\frac{S_1}{20}$ where S_1 is spacing of sprinklers along the line.

5. Multiply this by $\frac{40}{20} = 2$ to obtain correct loss for 40-foot spacing: $4.1 \times 2 = 8.2$ pounds per square inch.

When the size of pipe is reduced along the line, that is, when two or more sizes of pipe are used, the problem of determining the friction loss is more difficult. The procedure can best be explained by an example. Assume that a 1,000-foot line is composed of 320 feet of 3-inch pipe, 360 feet of 4-inch pipe and 320 feet of 5-inch pipe, with a total discharge of 375 gallons per minute. With sprinklers spaced 40 feet apart, a total of 25 sprinklers, the average discharge of the sprinklers would be 15 gallons per minute.

From figure 26, the friction loss in 3-inch pipe with $\frac{320}{40} = 8$ sprinklers would be about 1.4 pounds per square inch. This is multiplied by 2 to obtain the actual loss because the sprinkler spacing is 40 feet instead of 20 feet. The corresponding loss for 8 sprinklers, spaced 20 feet apart on 4-inch pipe is less than 1 pound per square inch, and cannot be determined from the graph. By extending the lines beyond the lower edge of the graph, this loss is estimated to be 0.5 pounds per square inch which makes the actual loss about 1 pound. The excess loss in the 3-inch pipe, compared with the 4-inch pipe, will be $2.8 - 1.0 = 1.8$ pounds. The loss in 680 feet of 4-inch pipe, with 17 sprinklers, is $2 \times 2.4 = 4.8$ pounds. The actual loss in the combination 3- and 4-inch line is then $1.8 + 4.8 = 6.6$ pounds. The corresponding friction loss in 680 feet of 5-inch pipe would be approximately $2 \times 1 = 2$ pounds. The excess for the 3- and 4-inch line as compared with 680 feet of 5-inch line is, therefore, $6.6 - 2 = 4.6$ pounds. The loss in 1,000 feet of 5-inch pipe (25 sprinklers) would be $2 \times 2.2 = 4.4$ pounds. The total loss in the 1,000-foot combination line is, therefore, $4.4 + 4.6 = 9.0$ pounds which is about the maximum permissible for efficient operation. Had 4-inch pipe been used for the entire line, the loss would have been $2 \times 7.2 = 14.4$ pounds per square inch.

Friction Loss in Nozzle Lines.—For nozzle lines of standard galvanized pipe, one can estimate the friction loss in a similar manner. Assuming that all the water flows to the end of the line, the friction loss can be determined from tables 5 or 6. This loss is then multiplied by the proper factor F (table 10) for $m = 1.85$ to obtain the actual friction loss in the nozzle line. To determine, for example, the friction loss in 100 feet of 1-inch pipe with nozzles having an average discharge of 0.25 gallon per minute, spaced 3 feet apart, the steps would be as follows:

1. Determine the total discharge, which is equal to $\frac{0.25 \times 100}{3} = 8.3$ gallons per minute.

2. Using table 6, for $C = 120$, we find that the friction loss H_f for 8.3 gallons per minute in 100 feet of 1-inch pipe is about 6.0 feet of head.

3. From table 10, $m = 1.85$, interpolating for 33 nozzles, $F = 0.366$.

4. The actual friction loss is, therefore, approximately $0.366 \times 6 = 2.2$ feet.

When several pipe sizes are used in a nozzle line, the problem of determining the friction loss is essentially the same as for a combination portable sprinkler line. Assume that a nozzle line is composed of 100 feet of 1½-inch pipe, 100 feet of 1¼-inch pipe, and 100 feet of 1-inch pipe, with nozzles delivering 0.25 gallon per minute spaced 3 feet apart. The total discharge would be 25 gallons per minute; 8.3 gallons per minute at 100 feet; and 16.7 gallons per minute at 200 feet. The friction loss in the 100 feet of 1-inch pipe, computed above, is 2.2 feet of head. Had this been 1¼-inch pipe, the loss would have been $0.366 \times 1.6 = 0.6$ feet. The excess loss for 1-inch pipe, as compared with 1¼-inch pipe, is therefore $2.2 - 0.6 = 1.6$ feet. For 200 feet of 1¼-inch pipe, the loss would be $0.36 \times 5.6 \times 2 = 4.0$ feet; for 200 feet of 1½-inch pipe, it would be $0.36 \times 2.6 \times 2 = 1.9$ feet. The excess for 1¼-inch pipe compared with 1½-inch pipe is $4.0 - 1.9 = 2.1$ feet. For 300 feet of 1½-inch pipe, the loss would be $0.35 \times 5.6 \times 3 = 5.9$ feet. The actual loss for the combination line would be the loss for 300 feet of 1½-inch pipe plus the excess losses due to reducing the size, or $5.9 + 2.1 + 1.6 = 9.6$ feet of head. This method of computing losses, though only approximate, is fairly reliable when the average nozzle discharge is known or can be determined. In order to limit the variation in discharge of the nozzles to 10 per cent, nozzle lines should be so designed that the friction loss does not exceed 20 per cent of the average operating head on the line.

Discharge, Pressure, and Power Requirement Relations for Sprinkler Lines.—Certain fundamental relations between pressure, discharge, and power requirement for sprinkler lines apply to all types of sprinkler systems. Although the friction loss in sprinkler lines depends only upon the flow of water in the pipe, this depends upon the discharge of the sprinklers, which, in turn, depends upon the pressure. We find, therefore, a relation between the friction loss and the pressure. To clarify these relations, we will start with the sprinkler-discharge equations 2 and 3, page 52, which show that the discharge of a sprinkler nozzle is proportional to the square root of the pressure at the sprinkler.

Expressed mathematically,

$$q = K\sqrt{P} \qquad (16)$$

where q is the discharge of the sprinkler, K is a proportionality factor depending upon the size of the sprinkler nozzles, and P is the pressure at the sprinkler.

Since the pressure along the line will vary because of the friction loss, the sprinklers will not all discharge the same amount of water as was assumed for the purpose of estimating the friction loss. However, the total discharge of all the sprinklers is also proportional to the square root of the pressure at any point on the line. If we assume that the exponent $m = 2$ (equations 9 to 15), it follows that the friction loss will be directly proportional to the pressure at any point on the line. If, for example, the pressure at the pump is doubled, the friction loss will be doubled, and the remaining pressure at the distal end of the line will also be doubled. The ratio of the pressure at any sprinkler to the pressure at any other sprinkler will therefore remain constant. For convenience, the *pressure ratio* will be defined as the ratio of the pressure at any sprinkler on the line to the pressure at the distal end of the line, and the *discharge ratio* as the ratio of the discharge of any sprinkler on the line to the discharge of the sprinkler at the distal end of the line. Thus there are definite pressure and discharge ratios for each sprinkler on the line; these remain constant regardless of the pressure. The discharge ratio is equal to the square root of the pressure ratio, thus

$$\frac{q}{q_0} = \sqrt{\frac{P}{P_0}} \tag{17}$$

where q is the discharge of any sprinkler at which the pressure is P, and q_0 is the discharge of the last sprinkler at the distal end of the line where the pressure is P_0. For pressure ratios less than 1.5, an approximate relation is

$$\frac{q}{q_0} = 1 + 0.5\left(\frac{P}{P_0} - 1\right). \tag{18}$$

Or, in words, the relative variation in the discharge of sprinklers along the line is about half of the relative variation in pressure. For example, a 20 per cent variation in pressure along the line will result in approximately 10 per cent variation in discharge of the sprinklers if all have the same nozzle sizes.

The average pressure along a sprinkler line, P_a, approximates the pressure at the distal end, P_0, plus one fourth the friction loss in the line, P_f; or expressed mathematically,

$$\left.\begin{aligned} &P_a = P_0 + 0.25\,P_f \text{ (approx.)} \\ \text{or}\quad &\\ &P_a = P_0 + 0.25\,(P_n - P_0) \text{ (approx.)} \end{aligned}\right\} \tag{19}$$

where P_n is the pressure at the sprinkler nearest the pump. Also, the

average discharge of the sprinklers can be expressed in terms of the discharge of the first and last sprinklers, by the equation

$$q_a = q_0 + 0.25 (q_n - q_0) \text{ (approx.)} \tag{20}$$

or in terms of the pressure at the first and last sprinklers, by the equation

$$q_a = q_0 \left[1 + 0.12 \left(\frac{P_n}{P_0} - 1 \right) \right] \text{ (approx.)} . \tag{21}$$

If the discharge of any sprinkler, q_1, at a given pressure, P_1, is known, then the discharge of the same sprinkler at pressure P_2, is given by the equation

$$q_2 = q_1 \sqrt{\frac{P_2}{P_1}} \tag{22}$$

and the average sprinkler discharge corresponding to a pressure P_2 at any point on the line can be expressed in terms of the average sprinkler discharge at pressure P_1 in a similar manner.

The total flow is the product of the average sprinkler discharge and the number of sprinklers on the line. Thus

$$Q = Nq_a = Nq_0 \left[1 + 0.12 \left(\frac{P_n}{P_0} - 1 \right) \right] \tag{23}$$

where Q is the total discharge, and N is the number of sprinklers.

When the sprinkler lines are so designed that the pressure ratio does not exceed 1.2, the variation in discharge of the sprinklers will not exceed 10 per cent, and the average discharge of the sprinklers will not exceed the minimum discharge by more than 2.4 per cent. Of course, variations in elevation along the line will affect both the pressure and the discharge of sprinklers.

The power requirement for pumping water for sprinkling depends upon the total pumping head and upon the total discharge of the line. The total head includes (1) the lift from the water surface in the well or ditch from which the water is pumped, (2) the friction losses in the suction pipe or hose, (3) the velocity head, and (4) the pressure at the pump. Where water is pumped from ditches, the lift and friction losses in the suction hose are small in comparison with the pressure head. For approximate calculations the velocity head may be neglected.

The horsepower requirement, hp., is given by the relation

$$\text{hp.} = \frac{QP_p}{1715E} \tag{24}$$

where Q is the discharge in gallons per minute, P_p is the total pumping

head, including lift and friction losses, expressed as pressure, and E is the efficiency of the pump, expressed decimally.

The following example illustrates the use of these equations. A line of 4-inch portable sprinkler pipe has thirty sprinklers, spaced 40 feet apart. The discharge capacity of each sprinkler is 15 gallons per minute at 40 pounds' pressure. The suction lift and the friction loss in the suction hose approximate 3 pounds per square inch. The pump is 40 feet from the nearest sprinkler, and the line is level. Assume a pump efficiency of 60 per cent. What will be the total discharge, the required pressure at the pump, and the horsepower requirement, for a minimum pressure at the distal end of the line of 40 pounds per square inch?

From figure 26, the friction loss for thirty sprinklers discharging 15 gallons per minute would be about 12 pounds per square inch. This must be multiplied by $\frac{40}{20} = 2$ to obtain 24 pounds per square inch, the actual loss. Since this calculation was based upon an average discharge of 15 gallons per minute, it corresponds to an average pressure of 40 pounds per square inch. The pressure at the distal end would be, from equation 19,

$$P_0 = P_a - 0.25\,P_f = 40 - \frac{24}{4} = 34 \text{ pounds per square inch.}$$

If the pressure at the distal end is increased to 40 pounds per square inch, as specified by the problem, the friction loss will increase in proportion, or

$$P_f = \frac{40}{34} \times 24 = 28 \text{ pounds per square inch.}$$

And the average pressure will be (equation 19)

$$P_a = 40 + \frac{28}{4} = 47 \text{ pounds per square inch.}$$

The pressure at the pump will then be

$$P_p = P_0 + P_f = 40 + 28 = 68 \text{ pounds per square inch.}$$

The average sprinkler discharge, from equation 22, will be

$$q_a = 15\sqrt{\frac{47}{40}} = 16.3 \text{ gallons per minute.}$$

The total discharge will be

$$Q = 16.3 \times 30 = 489 \text{ gallons per minute.}$$

The total pumping head (neglecting velocity head, but adding the suction lift) expressed as pressure, is

$$68 + 3 = 71 \text{ pounds per square inch.}$$

The horsepower requirement will be (equation 24)

$$\text{hp.} = \frac{489 \times 71}{1{,}715 \times 0.60} = 33.7.$$

An appreciable saving in power could be effected by using a split-line arrangement—that is, where the source (portable pumping plant) is at the center of the line the friction loss would be much less, and the sprinkler discharge fairly uniform along the line. According to calculations similar to those above, with two 600-foot lines, the total discharge would be 455 gallons per minute, the friction loss 3.4 pounds per square inch, the pressure at the pump 43.4 pounds per square inch, and the power requirement 20.5 horsepower.

Summarizing these principles, we can state:

The pressure at any point on the line is directly proportional to the pressure at any other point on the line, and a change in pressure at one point will result in a proportionate change in pressure at any other point.

The friction loss is directly proportional to the pressure at any point on the line, and a change in pressure at any point will result in a proportionate change in the friction loss.

The discharge of any sprinkler, and the total discharge, is proportional to the square root of the pressure; a change in pressure at any point on the line will result in a change in discharge proportional to the square root of the change in pressure.

The power requirement for pumping, being proportional to the product of the pressure and discharge, is proportional to the three-halves power of the pressure; a change in pressure at any point will result in a change in power requirement that is proportional to the three-halves power of the change in pressure.

DISTRIBUTION OF WATER FROM ROTATING SPRINKLERS

The purpose of a sprinkler is to distribute the water to the soil in the form of a sprinkle or spray so that it can be absorbed without running off. Preferably, the water should be distributed uniformly over the area. Since nearly all rotating sprinklers cover circular areas, an absolutely uniform application is not possible. The degree of uniformity obtainable depends primarily upon the type of distribution pattern produced and upon the spacing of sprinklers. Numerous other factors, such as wind, pressure, and uniformity of rotation of the sprinkler, affect distribution.

Many tests have been made to determine the uniformity of distribution. Manufacturers generally have facilities for testing sprinklers and making adjustments. A series of tests on both American and German sprinklers was conducted by Staebner.[18] These tests were made by catching the water in receptacles placed at various distances from the sprinkler. After the sprinkler had been operated for a specified time, the amount of water caught in each receptacle was measured to determine the depth. For most of his tests, Staebner used 112 cans and rain gauges distributed in a geometrical pattern over a square area, 100 feet on each side. Extensive tests have also been made in Germany,[19] using a large number of receptacles placed over the entire area covered.

Some manufacturers and experimenters have apparently been striving for a sprinkler that distributes a uniform amount over a large portion of the area covered, with a rather abrupt breaking off at the edges. Others have given more consideration to the effect of overlap and have tried to obtain a different pattern. Staebner judged the sprinklers tested on their ability to distribute water so that the maximum depth was not more than twice the minimum, except near the edges of the area covered; but he did not discuss the question of overlap nor of proper spacing for such sprinklers. He states, "No matter how successfully they may distribute water over a circular area, they leave much to be desired, because if circles just touch one another a considerable area is left unwatered, and if they overlap a great amount of double coverage results." He further concludes, "More uniform distribution over a large area can be obtained with the overhead-pipe system (nozzle lines) than with any other type of spray irrigation equipment now available."

Before 1932 slow-revolving sprinklers were used mostly for stationary overhead orchard systems and for irrigating large parks, golf courses, and the like. In such installations, the common practice is to place the sprinklers as far apart as possible and still cover all the ground. Sprinklers are generally mounted in either a square or a triangular arrangement, the distance between them being as much as 80 to 90 feet. In 1932, when portable systems first came into general use, the sprinklers, covering 100 to 120 feet circles, were usually spaced 40 feet apart on the pipe line, which was generally moved 50 to 60 feet for each setup. This provided more than a double overlap in both directions. With such close spacing it was assumed that the resulting distribution would be fairly uniform.

[18] Staebner, F. E. Tests of spray irrigation equipment. U. S. Dept. Agr. Cir. **195**: 1–29. 1931.

[19] Studiengesellschaft für Feldberegnung. Die Feldberegnung. RKTL Schriften heft **13**:1–177, 1930; heft **30**:1–176, 1932; heft **38**:1–177, 1933. Paul Parey, Berlin, Germany.

SPRINKLER TESTS AT DAVIS

To obtain definite information about the distribution of water under such conditions, and especially to determine the effect of wind, speed of rotation, and spacing of sprinklers upon the distribution, a series of tests on commercial sprinklers was made at Davis. For the first 122 tests, small rain gauges made from no. 2½ tin cans were placed 10 feet apart in each direction over the entire area covered by the sprinkler except on the north-south and east-west axes, where they were 5 feet apart. For sub-

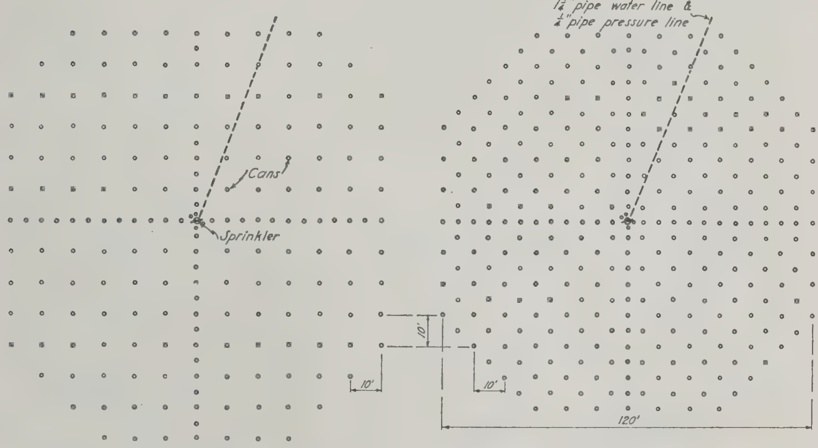

Fig. 27.—Arrangements of cans for sprinkler tests at Davis. Left, the layout for tests 1 to 122; and right, for tests 123 to 170.

sequent tests an additional can was placed in each square, one can being provided for each 50 square feet. Figure 27 shows the arrangements.

Water was supplied from the domestic system under a pressure of about 40 pounds per square inch. To increase this pressure when desired, a booster pump was provided. A 1-inch calibrated water meter measured the discharge from the sprinkler. There was a return pressure line from the base of the sprinkler riser, and a calibrated pressure gauge was installed near the pump and water meter. By means of a valve at this point it was possible to regulate and maintain at the sprinkler a constant pressure of any desired amount up to the maximum available. The arrangement proved highly satisfactory.

A standard Weather Bureau type four-cup anemometer was installed about 10 feet above the ground near the pump house, and the wind velocities given are those obtained at this location. The humidity and air temperature were determined with a sling psychrometer, readings being taken at intervals of 5 to 10 minutes during the tests.

About 130 tests on slow-revolving sprinklers have been made with these facilities. Some additional work with these sprinklers was done at Paradise, California. Lawn-sprinkler heads and small whirling sprinklers have also been studied. Some of the slow-revolving sprinklers are shown in figure 28. For most of these tests the sprinkler was operated for one hour. The water caught in the cans was measured to the nearest cubic centimeter, equivalent to $\frac{1}{200}$ inch in depth. All tests were plotted as in

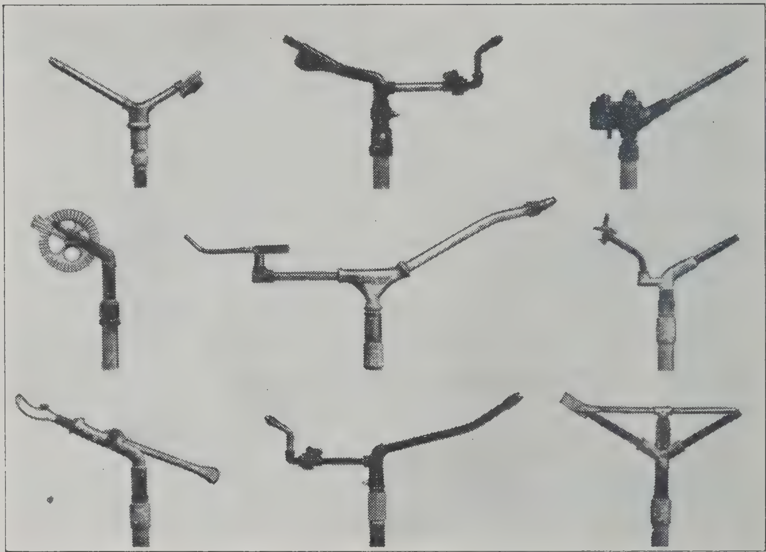

Fig. 28.—Some sprinklers of the slow-revolving type used on portable systems that were used in the tests for distribution of water. Some of these have been replaced by newer models.

figure 29 showing contours representing points of equal depth, and cross sections in both the north-south and east-west directions. From these tests a few have been selected to illustrate typical patterns for some of the sprinklers tested; and to illustrate the effect of wind, insufficient pressure, rapid rate of rotation, and variations in the rate of rotation.

Typical Distribution Patterns for Favorable Conditions.—Figures 29 to 33 illustrate typical distribution patterns for slow-revolving sprinklers operating under favorable conditions. For all but one of these tests the wind velocity averaged less than 3 miles per hour. The speed of rotation did not exceed one revolution per minute, and the pressure was ample for proper distribution. The essential data for each test are given in the figures and legends accompanying them. For four of the five patterns , the average diameter covered exceeds 120 feet. These distribu-

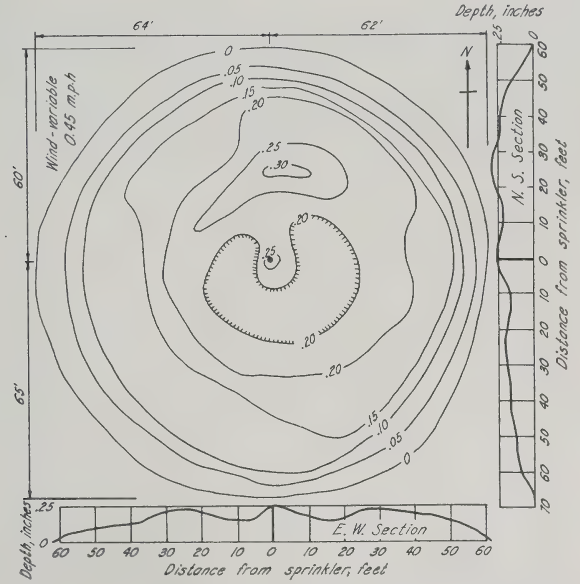

Fig. 29.—Test 16. Sprinkler, B-3; nozzles, 9/32 and 3/16 in. Test data: pressure, 45 pounds per sq. in.; discharge, 19.7 gal. per min.; average rate of rotation, 0.7 r. p. m. Conditions for test favorable.

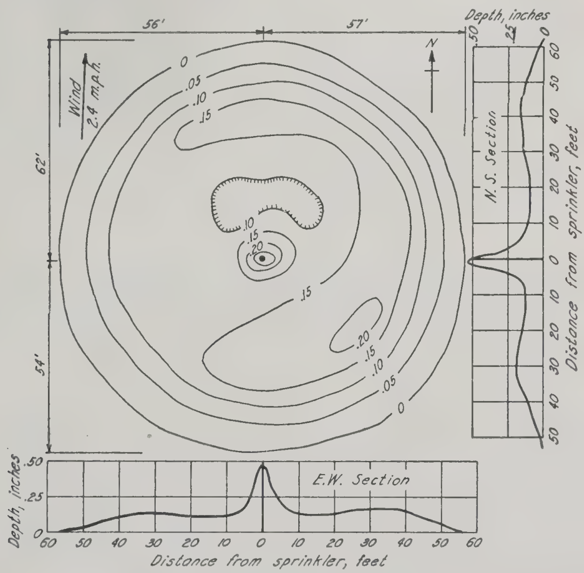

Fig. 30.—Test 90. Sprinkler, F-1; nozzles, 1/4 and 1/8 in. Test data: pressure, 40 pounds per sq. in.; discharge 14.3 gal. per min.; average rate of rotation, 1.0 r. p. m. Conditions for test favorable.

tion patterns are typical of a large number obtained and illustrate the uniformity of distribution obtainable with sprinklers operating under favorable conditions—that is, adequate pressure, low wind velocities, and proper speeds of rotation. Particular attention is called to figures 31 and 33, for which the cross sections are somewhat triangular. As will be shown later, this type of pattern produces the most uniform distribution

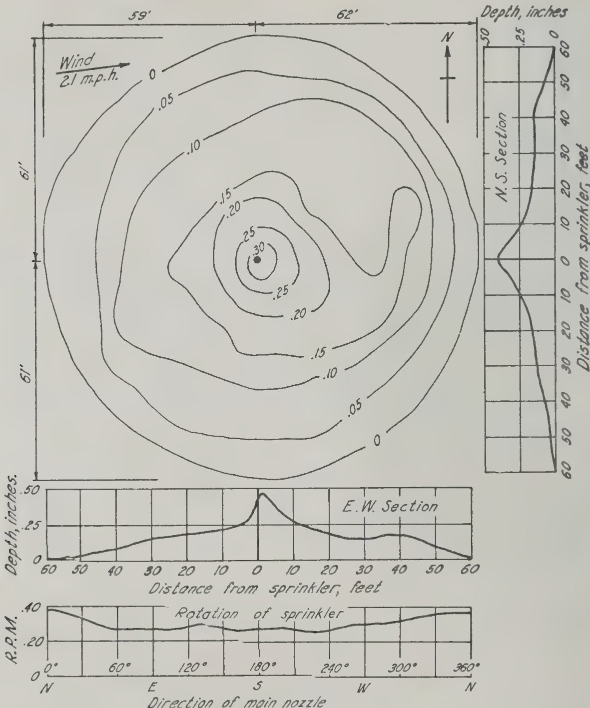

Fig. 31.—Test 132. Sprinkler, B-4; nozzles, 7/32 and 1/8 in. Test data: pressure, 50 pounds per sq. in.; discharge, 12.0 gal. per min.; average rate of rotation, 0.29 r. p. m. Conditions for test favorable. Lower profile shows variations in average rate of rotation for different positions of the main nozzle.

over a large area when the sprinklers are properly spaced. Figures 31 and 32 include a graphic record of the average rate of rotation as determined for each 30-degree angle of rotation. The variations in the rate of rotation were determined for most of the tests subsequent to test number 52. There was evidence that variations in rate of rotation were largely responsible for uneven distribution.

Effect of Low Pressure on Distribution from Sprinklers.—To determine the effect of low pressure, several tests were made at pressures

inadequate for proper distribution. Figures 34, 35, 36, and 37 illustrate typical patterns at pressures of 20 pounds per square inch. The most noticeable feature is the ring near the outside edge of the area covered, where the depth of application was several times greater than at a distance of 10 to 20 feet from the sprinkler. This doughnut or ring-shaped pattern resulting from low pressure is one that generally produces a

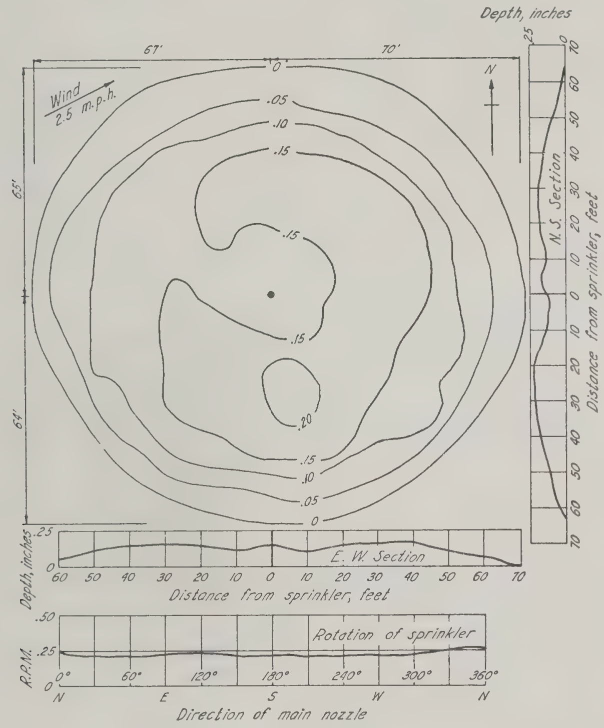

Fig. 32.—Test 136. Sprinkler, C-1; nozzles, 9/32 and 1/8 in. Test data: pressure, 50 pounds per sq. in.; discharge, 19.3 gal. per min.; average rate of rotation, 0.22 r. p. m. Conditions for test favorable.

very uneven distribution for all reasonable spacings of sprinklers. The effect of spacing on the distribution is discussed later in more detail.

Another noticeable feature of the lower pressure is the smaller area covered. The average diameter of the wetted area is 90 to 100 feet, as compared with diameters of more than 120 feet for pressures of 40 to 50 pounds and otherwise similar conditions. Judging from several tests on the same sprinkler at different pressures, the reduction in area covered is roughly proportional to the reduction in discharge of the sprinkler caused by the lower pressure, while the average actual rate of applica-

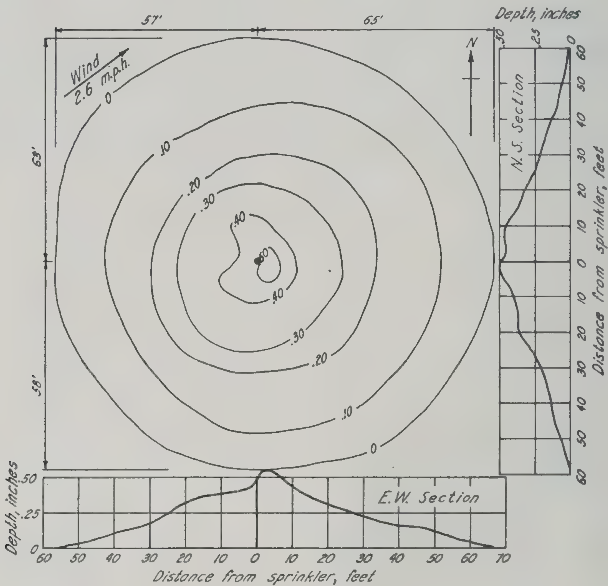

Fig. 33.—Test 170. Sprinkler, G-3; nozzles, ¼ and 7/32 in. Test data: pressure, 40 pounds per sq. in.; discharge, 19.3 gal. per min. Conditions for test favorable.

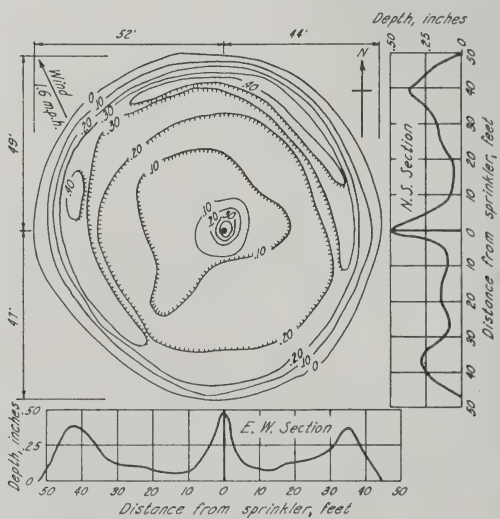

Fig. 34.—Test 11. Sprinkler, B-1; nozzles, 5/16 and 5/32 in. Test data: pressure, 20 pounds per sq. in.; discharge, 14.2 gal. per min.; average rate of rotation, 0.6 r. p. m. Pressure inadequate for good distribution.

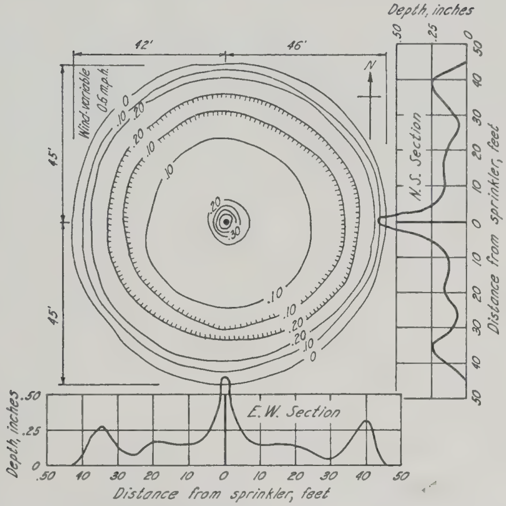

Fig. 35.—Test 31. Sprinkler, A-2 nozzles, ¼ and ³⁄₁₆ in. Test data: pressure, 20 pounds per sq. in.; discharge, 9.6 gal. per min.; average rate of rotation, 0.7 r. p. m. Pressure inadequate for good distribution.

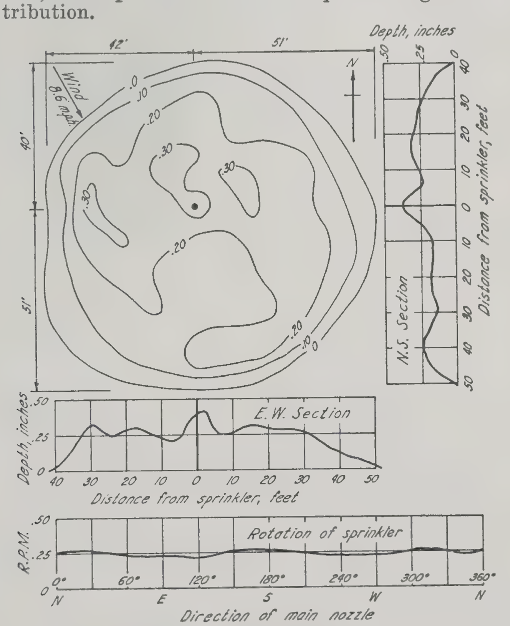

Fig. 36.—Test 102. Sprinkler, G-1; nozzles, ⁵⁄₁₆ and ⁷⁄₃₂ in. Test data: pressure, 20 pounds per sq. in.; discharge, 16.2 gal. per min.; average rate of rotation, 0.24 r. p. m. This sprinkler is equipped with a deflector on the tail nozzle which breaks up the jet and improves the pattern. Note the uniform rate of rotation.

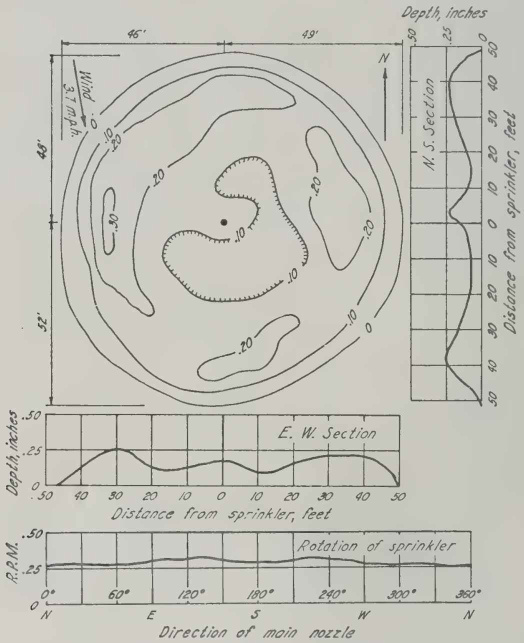

Fig. 37.—Test 140. Sprinkler, C-1; nozzles, 9/32 and 1/8 in. Test data: pressure, 20 pounds per sq. in.; discharge, 12.0 gal. per min.; average rate of rotation, 0.29 r. p. m. Pressure inadequate for good distribution.

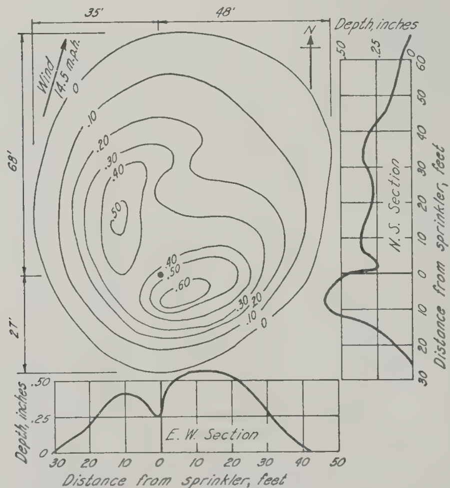

Fig. 38.—Test 58. Sprinkler, B-3; nozzles, 9/32 and 3/16 in. Test data: pressure, 40 pounds per sq. in.; discharge, 18.6 gal. per min. This pattern illustrates the effect of wind.

tion over the area covered, in inches (depth) per hour does not vary materially with a variation in pressure.

Effect of Wind on Distribution Patterns.—That wind exerts a major influence on the distribution pattern is illustrated by figures 38 to 41. Although the water is thrown somewhat farther in the leeward direction, it is thrown not nearly so far in other directions, and the area covered is appreciably reduced. There is generally a high concentration of water

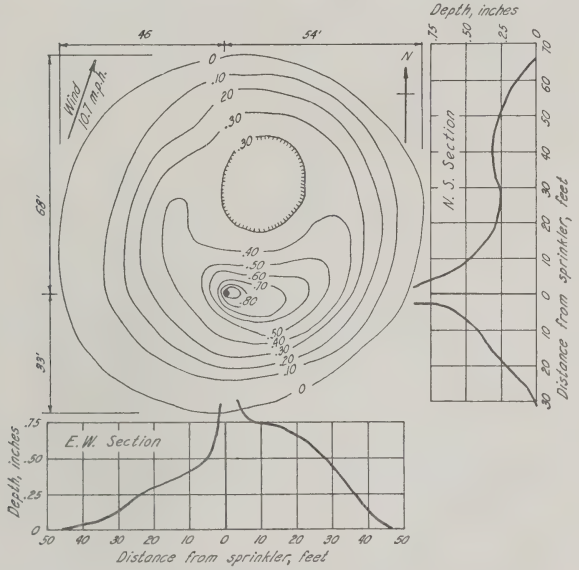

Fig. 39.—Test 88. Sprinkler F-1; nozzles, 5/16 and 1/8 in. Test data: pressure, 45 pounds per sq. in.; discharge, 21.9 gal. per min.; average rate of rotation, 2.6 r. p. m. This pattern illustrates the effect of wind.

near the sprinkler, especially in directions normal to the direction of wind, and a deficiency in the leeward direction.

The wind direction indicated is only approximate and was determined from the sprinkler pattern. For the first few tests the wind was observed at frequent intervals in order to estimate the approximate average direction. When, however, the shape of the sprinkler pattern proved to be a reliable integrated measure of the wind direction, observations for this purpose were discontinued.

Although the patterns appear very uneven, the effect of wind on the uniformity of distribution over a larger area, with sprinklers close enough together to provide an adequate overlap, is less serious than unevenness from other causes, such as variation in rate of rotation, because with wind the local areas of high and low concentrations always occur at the

same relative position with respect to the sprinklers and do not overlap on themselves and produce an exaggerated effect.

Effect of High Speed of Rotation on Distribution Patterns.—Figures 42, 43, and 44 illustrate how a high speed of rotation affects distribution. The most noticeable feature of these patterns is the large reduction in the area covered—a much greater reduction than results from a lowering

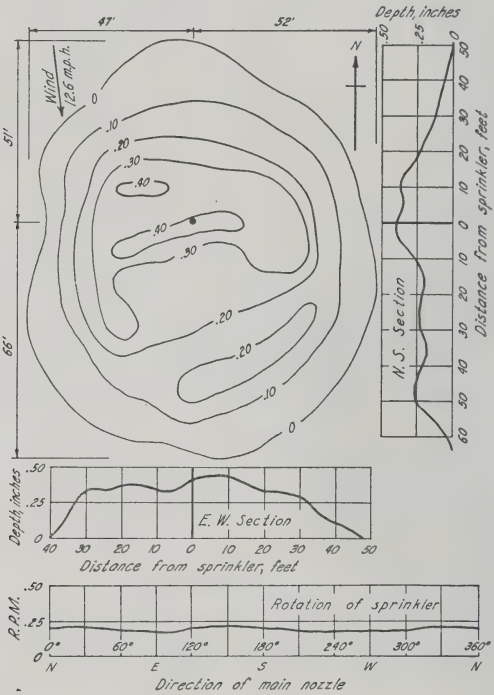

Fig. 40.—Test 100, Sprinkler, G-1; nozzles, 5/16 and 7/32 in. Test data: pressure, 30 pounds per sq. in.; discharge, 19.6 gal. per min.; average rate of rotation, 0.20 r. p. m. This pattern illustrates the effect of wind.

of pressure to any point for which reasonable distribution of water can be obtained. This reduction in area results in a corresponding increase in the actual rate of application, which exceeded 1 inch per hour in a localized area for one of the tests (fig. 43). This may be compared with an average rate of application of less than 1/4 inch per hour for the same sprinkler when rotating slowly. Obviously, sprinklers must be spaced much closer together, when rotating rapidly, to secure the same uniformity of distribution. In addition, with portable systems, the lines must be moved more frequently.

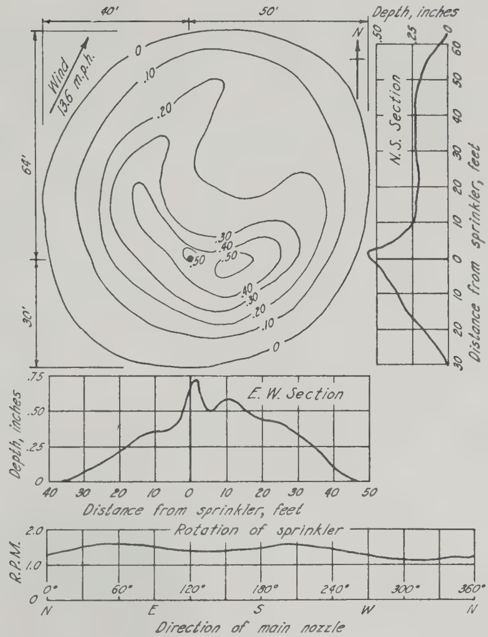

Fig. 41.—Test 112. Sprinkler I-1; nozzle, 5/16 in. Test data: pressure, 40 pounds per sq. in.; discharge, 22.7 gal. per min.; average rate of rotation, 1.3 r. p. m. This pattern illustrates the effect of wind.

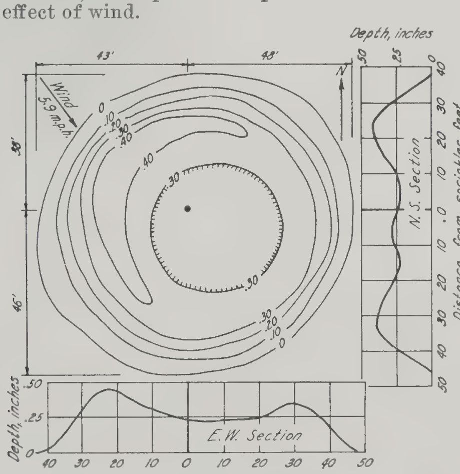

Fig. 42.—Test 21. Sprinkler B-2; nozzles, 9/32 and 5/32 in. Test data: pressure, 40 pounds per sq. in.; discharge, 17.5 gal. per min.; average rate of rotation, 13.6 r. p. m. This pattern illustrates the effect of high speed of rotation. Note the reduction in area covered and the corresponding increase in rate of application.

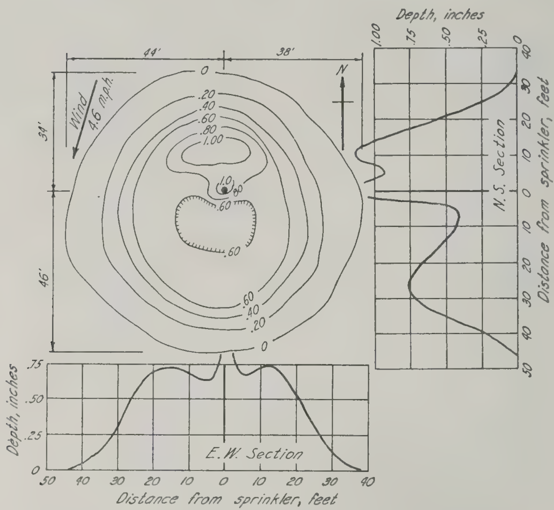

Fig. 43.—Test 118. Sprinkler, I-1; nozzle, 9/32 in. Test data: pressure, 46 pounds per sq. in.; discharge, 22.1 gal. per min.; average rate of rotation, 26.3 r. p. m. This pattern illustrates the effect of high speed of rotation.

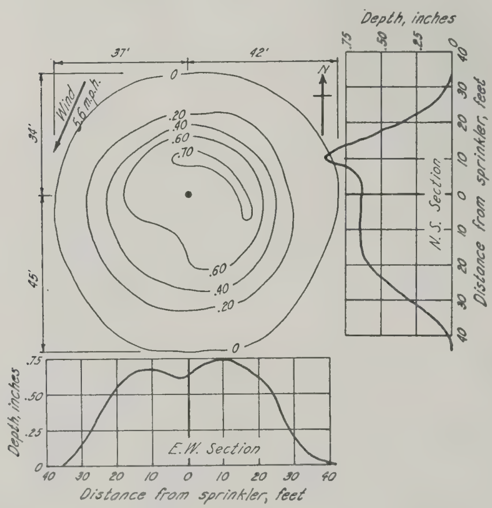

Fig. 44.—Test 149. Sprinkler, L-1; nozzle, 1/4 in. Test data: pressure, 50 pounds per sq. in.; discharge, 17.0 gal. per min.; average rate of rotation, 51.0 r. p. m. This pattern illustrates the effect of high speed of rotation.

Slow-revolving sprinklers are designed to be operated at speeds of about one revolution per minute, and should never rotate faster than three or four revolutions per minute. They are sometimes provided with a device for regulating the speed. Sometimes, however, they rotate very rapidly; in one instance a count showed a sprinkler on a portable system to be averaging 90 revolutions per minute. Rotation speeds of 20 revolutions per minute are common on many systems. Some sprinklers are so designed that the speed of rotation can be adjusted only within certain limits, or not at all, and high speeds are impossible. Excessive speeds increase the wear on the bearings and spindles, which in turn may cause the sprinkler to rotate unevenly.

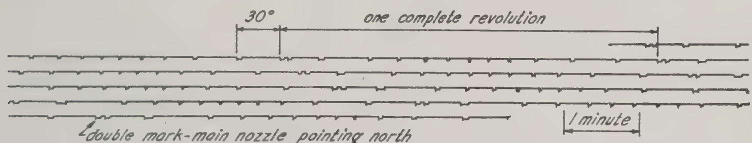

Fig. 45.—Recorder chart showing how variation in rate of rotation of sprinklers was determined. The pen makes a mark for each 30 degrees of rotation, a double mark for each revolution of sprinkler. Uneven spacing of marks shows variation in rate of rotation.

Effect of Variation in Rate of Rotation on Distribution Patterns.—Before very many tests had been made, it was apparent that some of the unevenness in distribution was caused by the sprinkler's rotating at a variable rate through each revolution. With rates less than one revolution per minute, this variation is not noticeable to the eye; but by timing the sprinklers through consecutive quadrants with a stop watch, it was found that there were appreciable variations in the average rate for the different quadrants. The rate was always slow or fast (as the case might be) for the same position of the sprinkler, that is, when a nozzle was pointing in the same direction, so that more water was being thrown in one direction from the sprinkler than in another. To investigate this point thoroughly, an anemometer recorder was converted into a rotation recorder by changing the gear ratio so that the drum turned at a peripheral speed of 1 inch in 50 seconds. A commutator arrangement was attached to the sprinkler so that an electrical circuit was shorted for each 30 degrees, or 60 degrees, of rotation as desired. For speeds exceeding about 1 revolution per minute, 60-degree intervals were used; for speeds of less than this amount, 30-degree intervals. This recorder operated successfully only when the sprinkler rotated at a speed of less than three revolutions per minute. The data were tabulated by measuring the number of seconds for each point of contact on the chart with a scale having 50 graduations per inch. The recorder was generally

operated 30 to 45 minutes during a test; and the data were tabulated for this period, or up to a maximum of 30 or 40 revolutions. The average rate of rotation for each 30- or 60-degree angle was calculated and plotted graphically as illustrated.

These determinations were made for most of the tests subsequent to test no. 52, except those for which the rate of rotation was too high to

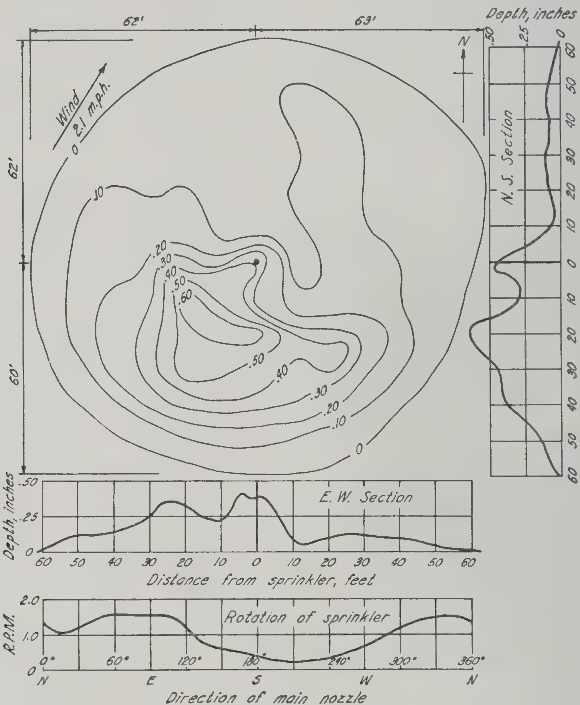

Fig. 46.—Test 103. Sprinkler, L-1; nozzles, 5/16 and 11/64 in. Test data: pressure, 40 pounds per sq. in.; discharge, 22.5 gal. per min.; average rate of rotation, 0.68 r. p. m. This pattern illustrates how a large variation in rate of rotation affects the distribution of water. Both nozzles of the sprinkler were pointing in approximately the same direction.

be determined. The apparatus for these tests and the method of analyzing the data proved very satisfactory, presenting definite evidence that uneven distribution in many tests was due largely to variations in the rate of rotation.

Figure 45 is a typical record of the rate of rotation as obtained with the recorder. The variation in rate is indicated by the difference in spacing between the marks on the lines.

Figures 46 and 47 illustrate how extreme variations in the rate of

rotation affect distribution. For figure 46, both nozzles of the sprinkler were discharging in approximately the same direction; and the local areas of high concentration to the southwest of the sprinkler are due to the very slow rate of rotation of the sprinkler when discharging in that direction, as indicated by the graphic record of the rotation. For figure 47 the two nozzles were discharging in approximately opposite direc-

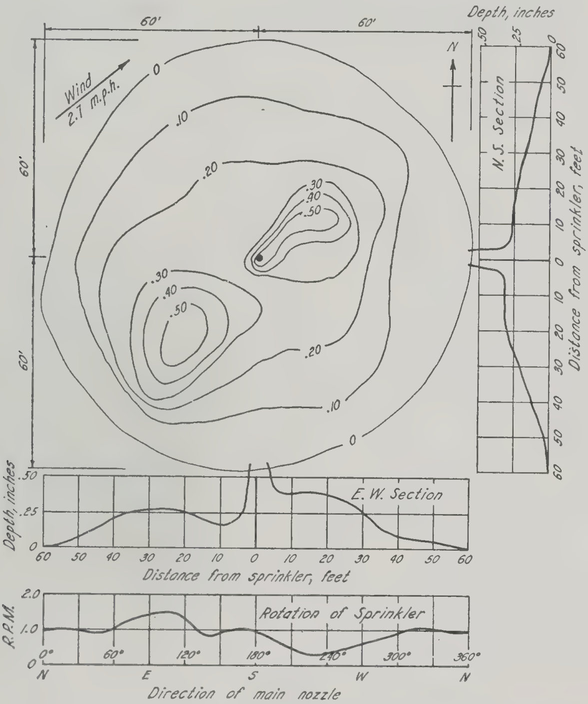

Fig. 47.—Test 115. Sprinkler, I-1; nozzle, 9/32 in. Test data: pressure, 50 pounds per sq. in.; discharge, 22.7 gal. per min.; average rate of rotation, 0.80 r. p. m. This pattern illustrates the effect of a variable rate of rotation. The two nozzles on this sprinkler were pointing in opposite directions; the high rate of application to the northeast of the sprinkler is due to the tail nozzle, while that to the southeast is due to the main nozzle.

tions; the high concentration to the northeast of the sprinkler is from the tail nozzle, whereas that in the southwest direction is from the main nozzle. That the lowest rate of rotation occurred for both tests (different sprinklers) when the main nozzle was pointing in a southwesterly direction was apparently accidental. Other tests indicated that the positions of maximum and minimum rates are apt to occur in any direction and that the variation is not due to wind, as some sprinkler users suppose.

Judging from tests on several different makes of sprinklers during strong winds—in one instance averaging more than 25 miles per hour—the positions of high and low speed bore no relation to wind direction, but could be altered at will by rotating the base of the sprinkler. One sprinkler was operated for a given period; then the base was oriented 180 degrees, and the test repeated. This caused the positions of high and low rates of rotation also to be oriented about 180 degrees, though the direction of the wind remained approximately the same (fig. 48).

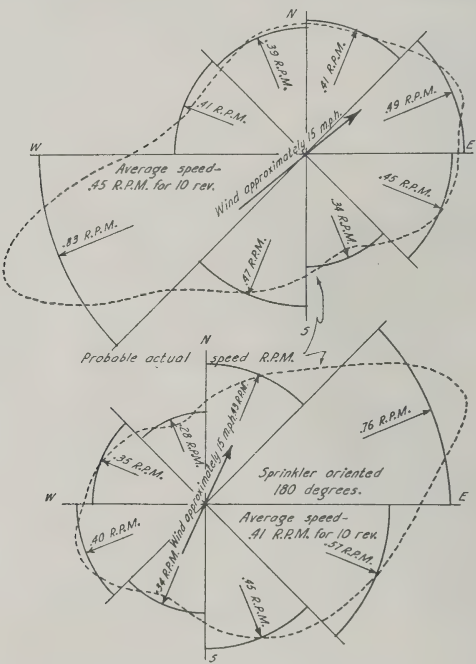

Fig. 48.—Variation in rate of rotation of sprinkler illustrated by plotting the rate as a radius. The similarity in shape and opposite orientation of the two diagrams indicates that the variation in rate of rotation was not caused by the wind.

Variations in rate of rotation is undoubtedly due to a variation in the friction on the bearing when the sprinkler is in different positions. Since the driving force is relatively constant, a variation in speed results when the frictional resistance varies. When operating under adequate pressure the frictional resistance for most sprinklers is sufficient so that the unbalanced torque, due to the wind reaction on the sprinkler, has little effect on the speed of rotation. Whether the variation in frictional resistance results from a lack of precision in manufac-

ture, from variations in thickness of the leather washer in the bearing, or from other causes was not determined. All sprinklers tested were new and unworn. Field observations indicate that worn sprinklers frequently vary more in speed of rotation than new sprinklers and that there is a great difference in the performance of sprinklers of the same kind on the same line.

DESIRABLE TYPES OF DISTRIBUTION PATTERNS AND PROPER SPACING OF SPRINKLERS

The distribution patterns in the foregoing figures immediately suggest two questions: What is the most desirable type of distribution pattern?

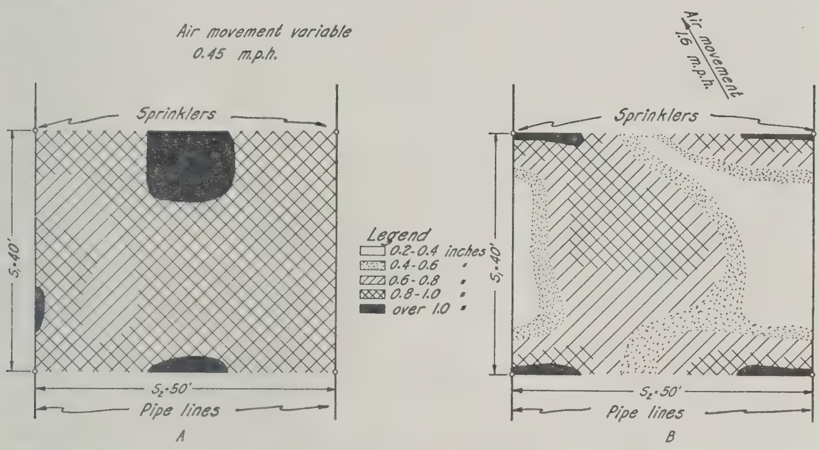

Fig. 49.—Resulting distribution of water when sprinkler patterns are overlapped to correspond to a spacing of 40 by 50 feet. *A*, Sprinkler pattern for test no. 16 (fig. 29) illustrates favorable conditions (pressure, 45 pounds per sq. in.). *B*, Pattern for test no. 11 (fig. 34) illustrates inadequate pressure (20 pounds per sq. in.).

What is the proper spacing of sprinklers for the most uniform distribution? All the sprinkler tests and many geometrical patterns were analyzed for the purpose of answering these basic queries.

To determine the uniformity of distribution for a group of sprinklers, some of the patterns were overlapped at a spacing of 40 feet in one direction by 50 feet in the other (a common arrangement for portable systems) and the resulting depth of application was calculated for points spaced 10 feet apart both ways. The application from all sprinklers affecting the net area was included. Figure 49 shows the results for two tests previously illustrated. For test no. 16, with the sprinkler operating under favorable conditions, the resulting distribution is remarkably uniform; but for test no. 11 (inadequate pressure) the variation is from about 0.2 inch to more than 1.0. This analysis, though it serves

to illustrate the distribution obtained for specific tests and spacings, does not answer the principal questions involved.

A Method of Analyzing Sprinkler Tests for Uniformity of Distribution.—To compare sprinkler patterns and to determine how various spacings affect the resulting distribution of water, one needs a numerical expression to serve as an index of the uniformity secured. For this purpose an expression called the uniformity coefficient (C_u) was adopted. The uniformity coefficient expressed as a percentage is defined by the equation

$$C_u = 100\left(1.0 - \frac{\Sigma x}{mn}\right) \qquad (25)$$

in which x is the deviation of individual observations from the mean value m, and n is the number of observations. An absolutely uniform application is then represented by a uniformity coefficient of 100 per cent; a less uniform application, by some lower percentage.

When the intensity of application at any number of equally spaced points over the entire area covered by a sprinkler is determined, the uniformity coefficient can be computed for any spacing (in either direction) that is a multiple of the spacing of the points of observation. Thus a complete analysis of one sprinkler pattern to determine the best spacing and the resulting uniformity of application involves numerous computations.

Uniformity coefficients have been determined both for actual sprinkler patterns and for various geometric patterns. The depths of application at uniformly spaced points over the net area covered by a sprinkler are first determined. Sufficient points are used so that the depth at any particular point may be considered the mean for the unit area represented by that point. For the actual sprinkler patterns, the amount of water caught in each of the cans spaced 5 or 10 feet apart in parallel rows is taken as an individual observation. The pattern is then overlapped on itself to correspond to any desired spacing, and the total amount for each point within the net area covered by one sprinkler is determined and tabulated. The mean depth of application is next determined, and the deviation from the mean at each point is calculated. About half of the points will have applications of more, and half of less, than the mean. These deviations are then totaled, and the uniformity coefficient is computed from equation 25. For each sprinkler pattern, a different value of the uniformity coefficient is obtained for each spacing; and since the spacing may be different in the two directions, many tedious calculations are required to analyze one sprinkler pattern completely and determine what spacing will give the best results and how uniform the distribution will be.

A short-cut method of determining the optimum spacings has been employed in analyzing all the sprinkler tests. This method is equivalent to spacing the sprinklers closely along the pipe line and then determining the uniformity coefficients for different spacings between lines. (S_1 is used to denote the spacing between sprinklers along the line, and S_2 the spacing between lines.)

When sprinklers are close together (say, $S_1 = 10$ feet), a strip of ground will be wet so that there will be little variation along lines drawn parallel with the line of sprinklers. The profile of water concentration across the wetted strip along any line drawn at a right angle to the pipe line can be determined by overlapping a sprinkler pattern upon itself corresponding to the designated sprinkler spacing (S_1). This is done by summing up the water caught in the cans in each of the parallel rows. The extra cans on the two diameters are omitted so that all cans used are equally spaced over the area. The tabulated sums are then combined, corresponding to various spacings (S_2) between lines, and the uniformity coefficient calculated. The coefficients thus determined represent a measure of uniformity in only one direction, not a measure of the uniformity for the net area covered by sprinklers spaced normal distances along the line. Since the actual sprinkler patterns are not symmetrical, because of wind and other influences, the uniformity coefficients were determined for two directions normal to each other, and the mean value for each spacing was used. These analyses indicate the optimum spacings, which apply both along the lines and between lines.

Distribution for Geometrical Patterns.—Before discussing the results of the analyses of the actual sprinkler tests, we may well consider the distribution for certain geometrical patterns. If a sprinkler is rotated at a uniform speed in perfectly still air, the resulting pattern will be symmetrical about the center. Several symmetrical patterns representing different geometric shapes have been analyzed to determine the uniformity of distribution for various spacings. Six of these patterns, some being typical of actual sprinkler patterns, are shown in figure 50, together with the uniformity coefficients for different values of S_2 when S_1 equals 5 per cent of the diameter covered. The distribution for pattern B is nearly uniform for all values of S_2 up to 55 per cent of the diameter. Patterns A and C give fairly uniform applications for all spacings up to 65 per cent of the diameter; beyond this the uniformity drops off rapidly. Patterns D and E produce a fairly uniform distribution for spacings of 75 and 80 per cent; but for spacings of 45 to 70 per cent there is an appreciable variation. Pattern F results in poor distribution for spacings of 50 to nearly 80 per cent, with only fair uniformity for spacings between 80 and 85 per cent of the diameter.

The uniformity coefficients for various spacings in both directions for patterns B and E, shown in figure 50, are given in table 11. This table illustrates how the uniformity coefficients vary with S_1 as well as with S_2. For pattern B the uniformity coefficients remain constant as S_1 is increased from 5 up to about 60 per cent of the diameter. For pattern E, however, with the spacing S_1 equal to 5 per cent of the diameter, (0.05 D), the uniformity coefficient drops from 97 when S_2 is 0.4 D, to

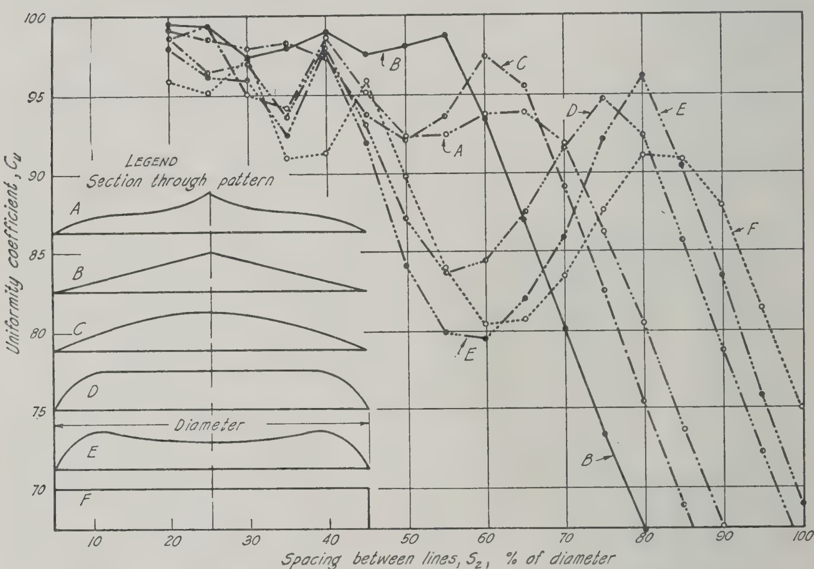

Fig. 50.—Geometrical sprinkler patterns and uniformity coefficients for different spacings of lines with sprinklers spaced closely along the lines. The higher the uniformity coefficient, C_u, the more uniform the application.

80 when S_2 is 0.6 D, and back up to 96 when S_2 is 0.8 D. For a spacing between lines, S_2, of 80 per cent of the diameter, the uniformity coefficient drops from 96 when S_1 is 0.05 D to 68 when S_1 is 0.6 D, then rises to 74 when S_1 is 0.8 D for a square arrangement, and to 83 when S_1 is 0.8 D for a triangular arrangement. In general, these and other patterns studied in detail indicate that the analyses for S_1 equals 0.05 D or 0.1 D (the short-cut method) are reliable for determining optimum spacings, and that fairly uniform distribution results when S_1 does not exceed half the optimum values of S_2. If, for example, a spacing of 0.05 D by 0.8 D shows a high uniformity coefficient, a spacing of 0.4 D by 0.8 D is likely to give good results. When a fairly close spacing between pipe lines is permissible, as it sometimes is on portable systems, excellent results can be obtained with patterns similar to D and E when the spacing

between lines, S_2, is also half the maximum optimum spacing as indicated by this method of analysis. This spacing provides in effect, a double overlap in both directions.

Desirable Patterns for Square and Equilateral-Triangle Arrangements of Sprinklers.—On stationary sprinkling systems, for economic

TABLE 11

UNIFORMITY COEFFICIENTS FOR VARIOUS ARRANGEMENTS AND SPACINGS OF GEOMETRICAL PATTERNS B AND E*

Spacing along line, S_1, in per cent of diameter, D	Spacing between lines, S_2, in per cent of the diameter, D				
	40 per cent	50 per cent	60 per cent	70 per cent	80 per cent
Pattern B					
5	99	98	93	80	67
20	99	98	93	80	67
30	98	97	93	80	67
40	97	96	93	80	67
50	..	96	93	80	67
60	..	..	91	80	67
60 T†	..	..	92	80	67
70	..	..	..	77	65
70 T	..	..	..	78	65
80	..	..	..	..	58
80 T	..	..	..	..	60
Pattern E					
5	97	84	80	86	96
20	96	84	80	86	94
30	93	83	80	85	93
40	96	83	77	83	88
50	..	76	77	82	81
60	..	..	75	71	68
60 T	..	..	67	66	70
70	..	..	..	66	67
70 T	..	..	..	65	73
80	..	..	..	..	74
80 T	..	..	..	..	83

* Shapes of patterns are shown in figure 50.
† T denotes a triangular arrangement of sprinklers; all others are rectangular.

reasons, sprinklers are usually spaced as far apart as possible in either a square or an equilateral triangle arrangement. One should know what patterns will give most uniform application, and how far apart sprinklers can be placed with satisfactory results. To answer these questions, a set of patterns that give as nearly uniform applications as possible for different spacings have been developed.

As previously shown, a conical pattern (pattern B in fig. 50) with a triangular cross section gives nearly uniform applications for spacings

up to about 55 or 60 per cent of the diameter. Slightly modified patterns of this general shape result in even greater uniformity for similar spacings. Figure 51 shows a series of curves illustrating half cross sections of patterns, as determined by trial and error methods, that give maximum uniformity coefficients for spacings of 50 to 75 per cent of the diameter when the sprinklers are arranged in a square. When the spacing exceeds 71 per cent of the diameter, the application at the center of the square between four sprinklers will be zero regardless of the shape of the

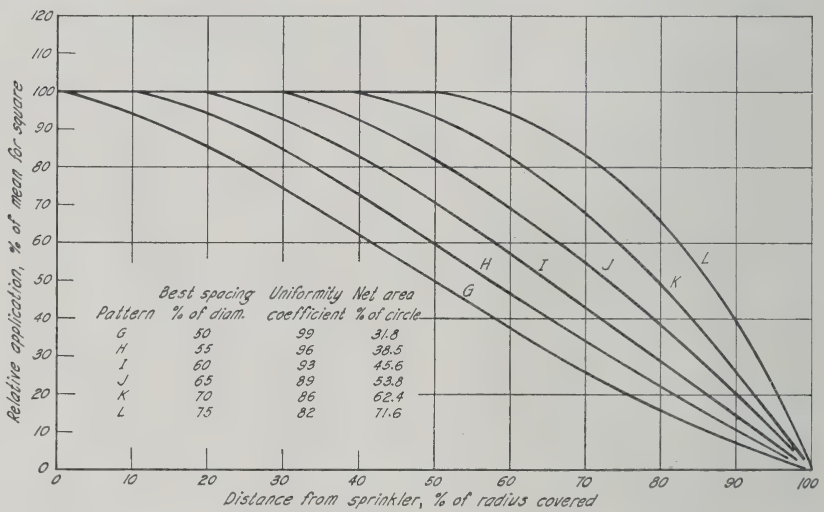

Fig. 51.—Half cross sections of patterns that give maximum uniformity coefficients for different spacings of sprinklers when arranged in a square.

pattern. A spacing of 71 per cent of the diameter is therefore the maximum possible if all the area is to be covered.

Detailed analyses of three of these patterns, G, I, and K, have been made for square spacings ($S_1 = S_2$) from 35 to 75 per cent of the diameter. Table 12 gives the uniformity coefficients for these patterns both for square spacing and for a very close spacing along the line ($S_1 = 0.05\,D$) for various spacings between lines. Data in table 12 are shown graphically in figure 52 which illustrates the relation between the uniformity coefficients obtained for square spacing and for close spacing along the line. In addition, the uniformity coefficients are shown for pattern K for $S_1 = 0.4\,D$. For pattern G the curves are similar, the close spacing showing slightly higher uniformity coefficients for all spacings between lines. For pattern I there is somewhat more difference between the curves, 60 per cent spacing between lines ($S_2 = 0.6\,D$) giving the highest uniformity coefficients for close spacing, whereas for the square arrange-

ment a 55 per cent spacing ($S_1 = S_2 = 0.55\ D$) gives the best results. For pattern K, the most desirable pattern for a spacing of 70 per cent ($S_1 = S_2 = 0.7\ D$), there is still more difference. When $S_1 = 0.05\ D$ much better results are obtained for values of S_2 between 60 to 70 per cent of the diameter than for spacings of 45 to 60 per cent, whereas for a square arrangement the uniformity coefficients are fairly constant

TABLE 12

UNIFORMITY COEFFICIENTS FOR PATTERNS G, I, AND K*

Spacing between lines, S_2, in per cent of diameter	Net area, in per cent of circular area covered	Uniformity coefficients, in per cent, for the patterns:		
		G	I	K
For square arrangement of sprinklers ($S_1 = S_2$)				
35	15.4	99	97	97
40	20.1	96	96	95
45	25.4	97	92	87
50	31.8	*99*†	98	86
55	38.5	93	96	87
60	45.6	85	*93*	87
65	53.8	78	87	85
70	62.4	69	80	*86*
75	71.6	..	72	80
For close spacing along the line ($S_1 = 0.05D$)				
50	3.2	*100*	94	89
55	3.5	95	97	90
60	3.8	89	*98*	93
65	4.1	82	92	97
70	4.5	74	85	*94*
75	4.8	..	78	87
80	5.1	..	..	80

* Shapes of patterns are shown in figure 51.

† Italicized figures correspond to the spacing for which the pattern is designed.

for all spacings between 45 and 70 per cent of the diameter. The curve for a 40 per cent spacing along a line ($S_1 = 0.4\ D$) is very similar to that for close spacing ($S_1 = 0.05\ D$) indicating that for customary spacings of sprinklers on portable systems, the results of analyses for close spacings along the line show what spacings between lines, S_2, will give the best distribution.

For an equilateral-triangle arrangement of sprinklers, patterns of a slightly different shape give better distribution. Figure 53 shows half cross sections of nine patterns that give the highest uniformity coefficients for spacings between sprinklers, S_1, of 50 to 90 per cent of the diameter. For this arrangement the spacing between parallel rows of sprinklers, S_2, is only 86.6 per cent of the spacing between sprinklers.

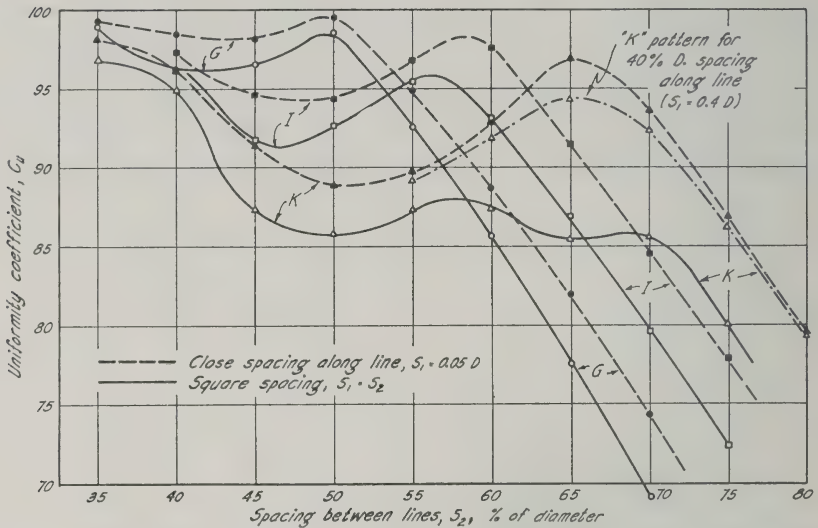

Fig. 52.—Uniformity coefficients for patterns G, I, and K (fig. 51) for close spacing along the line and for square spacing of sprinklers.

Table 13 gives the uniformity coefficients for four of these patterns—M, O, Q, and S for both a triangle arrangement and for close spacing along the line. The uniformity coefficients for both arrangements are compared in figure 54 for patterns M and S. There is a striking similarity in the two curves for both patterns. Uniformity coefficients for the close

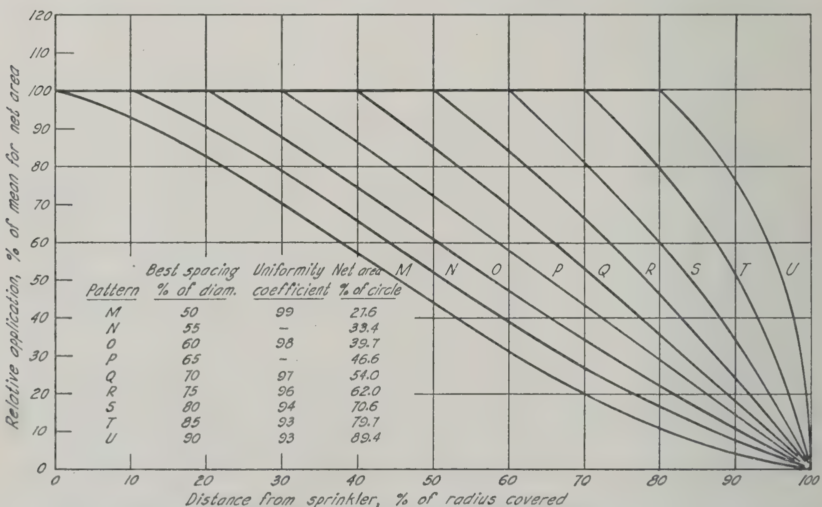

Fig. 53.—Half cross sections of patterns that give highest uniformity coefficients for equilateral-triangle arrangement of sprinklers with different spacings.

spacing ($S_1 = 0.05\ D$), though somewhat higher than for the equilateral-triangle arrangement with $S_1 = 0.866\ D$, do, however, indicate the spacings between lines, S_2, for triangular arrangements that give the best distribution.

TABLE 13

UNIFORMITY COEFFICIENTS FOR PATTERNS M, O, Q, AND S*

Spacing between sprinklers, S_1, in per cent of diameter	Spacing between lines, S_2, in per cent of diameter	Net area, in per cent of circular area covered	Uniformity coefficients, in per cent, for the patterns:			
			M	O	Q	S
For equilateral-triangle arrangement of sprinklers ($S_1 = 0.866\ D$)						
30	26.0	9.9	99	99	99	*99*
35	30.3	13.5	97	98	98	94
40	34.7	17.6	99	98	99	95
45	39.0	22.3	99	98	94	97
50	43.3	27.6	*99*†	96	89	89
55	47.7	33.4	97	96	87	82
60	52.0	39.7	91	*98*	88	78
65	56.3	46.6	82	94	92	78
70	60.7	54.0	72	87	*97*	82
75	65.0	62.0	..	77	90	89
80	69.3	70.6	..	67	79	*94*
85	73.7	79.7	..	..	68	86
90	78.0	89.4	..	..	..	73
For close spacing along the line ($S_1 = 0.05\ D$)						
5	40	2.5	99	98	95	97
5	45	2.9	*99*	97	92	91
5	50	3.2	96	98	92	87
5	55	3.5	90	*98*	94	87
5	60	3.8	84	93	*99*	90
5	65	4.1	77	86	94	94
5	70	4.5	69	78	87	*96*
5	75	4.8	62	72	80	90
5	80	5.1	..	65	72	83
5	85	5.4	..	..	66	77
5	90	5.7	..	..	..	69

* Shapes of patterns are shown in figure 53.
† Italicized figures correspond to the spacing for which the pattern is designed.

Judging from these studies, a more uniform application can be obtained with a triangular arrangement of sprinklers than with a square arrangement. This is particularly true for the wider spacings. A comparison of the uniformity of distribution obtainable with both arrangements is shown in figure 55. The points plotted correspond to the pattern giving the highest uniformity coefficient for each spacing. To secure any added benefit from the triangular arrangement, however, the sprinklers must be more accurately spaced than for the square arrangement. A comparison of patterns K and S will illustrate this point. Pattern S

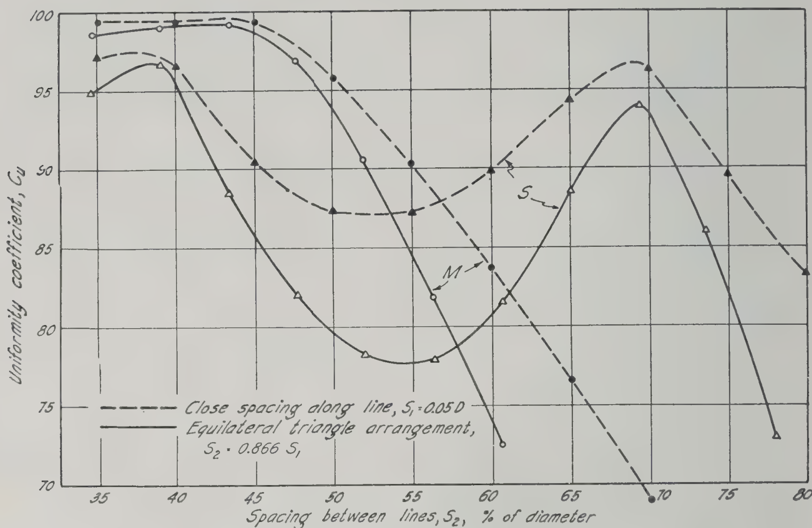

Fig. 54.—Uniformity coefficients for patterns M and S (fig. 53) both for close spacing along the line and for equilateral-triangle spacing of sprinklers. Note particularly that although pattern S gives a fairly high uniformity coefficient for a spacing of 70 per cent of the diameter covered by the sprinkler, the uniformity coefficient is fairly low for spacings between 40 and 65 per cent of the diameter.

has a uniformity coefficient of 94 for a triangular arrangement with $S_1 = 0.8\ D$, which corresponds to a net area of 70.1 per cent of the circular area covered by the sprinkler. Pattern K has a uniformity coefficient of only 86 per cent for a square spacing of 0.7 D, which corresponds

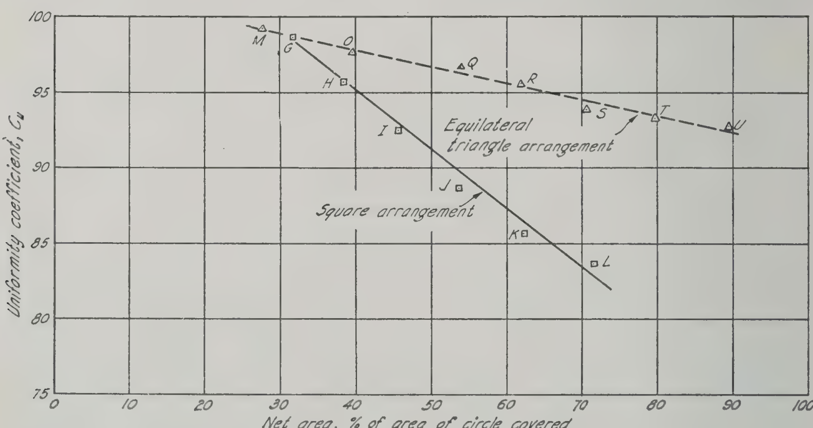

Fig. 55.—Comparison of highest uniformity coefficients for different patterns for square and equilateral-triangle arrangements of sprinklers. Higher uniformity coefficients can be obtained for the triangular arrangement when the sprinklers are correctly spaced.

to a net area of 62.4 per cent. When the spacing between sprinklers for pattern S is changed to 0.65 D, the uniformity coefficient drops to 78 per cent, whereas for pattern K, the uniformity coefficient remains above 85 per cent for all square spacings closer than 70 per cent.

UNIFORMITY OF DISTRIBUTION AND EFFECT OF SPACING ON ACTUAL SPRINKLER PATTERNS

A study of geometrical patterns to determine the uniformity of distribution is not entirely adequate, since actual sprinkler patterns are never symmetrical in shape because of wind and sometimes because of variations in the speed of rotation. To determine the uniformity of distribution corresponding to the actual sprinkler patterns, all of the tests suitable for this purpose were analyzed. The uniformity coefficients, corresponding to a spacing, S_1, of 10 feet along the line and spacings between lines, S_2, of 20 to 100 feet, were computed for both the east-west and north-south directions. Table 14 gives the mean uniformity coefficient for each spacing for the two directions, together with other pertinent data.

These data are summarized in table 15, where several tests on a given sprinkler under similar conditions of wind, pressure, and rate of rotation are averaged.

Table 16 gives the uniformity coefficients for various spacings along the line and between lines for sprinkler patterns illustrated in figures 29, 31, 33, 34, 39, and 43.

This table brings out several important facts regarding the uniformity of application of water by sprinklers. A comparison of the uniformity coefficients for tests 16, 132, and 170 for specific spacings will illustrate the effect of shape of pattern. For test 16, the optimum spacing S_2 is 80 to 90 feet; for spacings 60 and 70 feet, there is excessive overlap, and the uniformity coefficient is somewhat lower. This characteristic is not evident for tests 132 and 170 (patterns triangular in shape) but the optimum spacing is reduced to about 60 feet. The coefficients for test 11 illustrate the effect of inadequate pressure (20 pounds per square inch). For this pattern a fairly good distribution is obtained with a spacing of 10 by 80 feet, but when the spacing S_1 is 40 feet, the results are very poor for all spacings S_2, the coefficient being only 57 for a spacing of 40 by 80 feet. For test 170, the uniformity coefficients remain practically constant for any spacing S_2 when the spacing S_1 is increased from 10 feet up to 60 feet. The uniformity coefficients for test 88 (fig. 39), showing the performance of a sprinkler with a wind velocity of 10.7 miles per hour and for test 118 (fig. 43) where the sprinkler rotated rapidly (26.3 revolutions per minute), indicate to what extent the effective area

TABLE 14

SUMMARY OF SPRINKLER TESTS GIVING PERTINENT DATA TOGETHER WITH THE CALCULATED UNIFORMITY COEFFICIENTS FOR DIFFERENT SPACINGS BETWEEN SPRINKLER LINES

Test no.	Sprinkler designation	Nozzle diameters, inches		Pressure, pounds per square inch	Discharge, gallons per minute	Rate of rotation, revolutions per minute	Wind, miles per hour	Diameter of pattern, feet		Uniformity coefficients, in per cent, for various spacings between sprinkler lines, S_2								
								North-south	East-west	20 feet	30 feet	40 feet	50 feet	60 feet	70 feet	80 feet	90 feet	100 feet
3.........	A-1	1/4	3/16	41	14.1	2.0	1.5	100	94	95	87	88	93	86	81	72	..	..
4.........	A-1	1/4	3/16	51	15.7	0.6	2.7	111	100	98	96	94	92	90	88	79	68	58
5.........	B-1	5/16	5/32	40	20.5	0.45	0.5	132	133	99	98	96	94	92	82	81	86	92
6.........	B-1	5/16	5/32	40	20.4	0.4	7.2	120	107	97	99	93	87	87	91	88	77	64
7.........	B-1	5/16	5/32	30	17.7	0.5	4.3	121	115	98	95	94	89	82	85	92	88	77
8.........	B-1	5/16	5/32	40	20.3	0.4	11.4	114	90	98	96	89	79	80	86	79	67	..
9.........	B-1	5/16	5/32	40	20.4	0.4	15.5	93	89	100	98	89	82	89	83	66	..	..
10.........	B-1	5/16	5/32	40	20.3	0.3	13.0	107	97	98	95	93	89	86	87	84	71	60
11.........	B-1	5/16	5/32	20	14.2	0.6	1.6	96	96	89	89	85	80	69	75	84	82	..
12.........	B-2	7/32	5/32	40	12.0	0.6	2.5	105	106	99	96	92	88	90	90	81	68	..
13.........	B-3	9/32	3/16	40	18.5	0.5	9.5	96	102	99	96	87	83	88	79	65	..	..
14.........	B-3	9/32	3/16	40	18.5	0.5	2.0	124	127	98	97	95	95	86	84	89	91	84
15.........	B-3	9/32	3/16	45	19.7	0.6	4.2	112	116	99	99	95	86	87	90	84	72	60
16.........	B-3	9/32	3/16	45	19.7	0.7	0.4	125	126	99	98	96	95	88	87	90	92	83
17.........	B-3	9/32	3/16	30	16.1	0.4	3.1	114	115	99	98	95	86	83	90	94	82	70
18.........	B-3	9/32	3/16	25	14.7	0.4	3.3	106	94	99	97	90	78	79	88	85	72	..
19.........	B-2	9/32	5/32	40	17.4	6.4	7.6	100	101	98	94	94	85	84	88	80	68	..
20.........	B-2	9/32	5/32	40	17.5	6.0	2.6	98	95	99	93	93	78	80	91	85	70	..
21.........	B-2	9/32	5/32	40	17.5	13.6	5.9	84	91	99	96	82	82	90	88	75	..	..
22.........	B-2	9/32	5/32	40	17.5	2.5	1.7	104	96	96	95	93	86	76	81	89	85	71
23.........	B-2	9/32	3/16	45	19.7	1.2	1.8	114	115	98	94	91	91	80	79	86	89	81
24.........	B-2	9/32	3/16	40	18.5	0.9	2.0	115	118	98	96	83	93	83	82	89	93	85
25.........	B-2	9/32	3/16	25	14.8	0.5	2.0	100	101	91	96	89	79	69	75	86	86	72
26.........	C-1	9/32	1/8	40	16.4	1.9	1.7	121	119	98	98	92	95	91	89	91	87	79
27.........	C-1	9/32	1/8	50	18.1	3.2	4.0	104	115	98	97	96	91	90	93	87	71	..

28........	C-1	9/32	1/8	25	13.1	3.9	1.0	107	105	94	98	92	94	84	89	91	85	73
29........	A-2	1/4	3/16	40	13.5	1.0	10.0	90	79	96	96	87	88	79	63	..	..	..
30........	A-2	1/4	3/16	30	11.6	0.8	3.2	96	97	98	96	98	89	92	87	77	..	..
31........	A-2	1/4	3/16	20	9.6	0.7	0.6	90	88	94	89	88	91	79	79	82	74	..
32........	D-1	17/64	5/32	40	16.5	3.0	1.5	105	102	95	86	91	92	86	86	81	71	..
33........	D-1	17/64	5/32	25	13.2	2.5	1.2	93	93	97	81	91	87	75	81	83	..	..
34........	E-1	7/32	....	40	8.2	0.9	1.4	86	91	89	87	85	71	74	81	75	..	..
35........	E-1	7/32	....	60	10.2	1.2	1.0	102	106	100	96	96	81	79	86	89	78	..
36........	B-2	9/32	3/16	40	17.7	2.6	1.0	103	103	99	93	95	80	80	92	90	80	61
37........	B-2	9/32	3/16	40	17.6	0.4	0.4	120	119	98	92	93	93	83	79	84	86	90
38........	B-2	9/32	3/16	40	17.5	0.5	5.3	112	103	97	95	90	83	82	89	85	74	60
39........	B-2	9/32	3/16	40	17.7	0.5	0.7	122	121	98	93	91	96	87	79	82	88	91
40........	H-1	1/4	5/32	40	15.2	2.4	0.7	113	116	88	84	86	86	76	78	83	78	..
54........	B-3	9/32	5/32	40	17.5	0.46	4.4	112	108	99	97	97	87	86	93	90	76	63
55........	B-3	9/32	5/32	50	17.0	2.5	6.5	100	97	98	98	92	90	90	80	65	53	..
56........	B-3	1/4	5/32	40	15.2	0.9	8.7	98	82	99	93	85	85	86	75	61	42	..
57........	B-3	1/4	5/32	40	15.2	1.0	12.9	88	77	99	93	84	87	84	71	61	..	..
58........	B-3	9/32	3/16	40	18.6	....	14.5	95	83	96	94	88	88	80	67	54	..	..
59........	B-3	9/32	3/16	40	18.9	....	16.7	93	90	99	95	84	84	86	75	60	..	..
67........	B-2	5/16	5/32	45	20.8	3.2	2.3	112	110	98	98	96	85	77	80	90	89	76
68........	B-2	9/32	3/16	35	16.6	2.1	3.7	107	107	98	98	96	86	84	84	87	78	65
83........	F-1	1/4	1/8	29	12.2	1.0	9.1	99	88	96	92	89	84	88	87	74	..	..
84........	F-1	1/4	1/8	27	12.2	0.9	8.7	94	85	97	90	88	81	87	88	75	..	..
85........	F-1	1/4	1/8	28	12.2	0.9	4.4	90	94	95	89	89	82	83	84	74	62	..
86........	F-1	1/4	1/8	40	14.2	1.6	3.0	107	104	97	92	94	91	86	86	83	73	..
87........	F-1	1/4	1/8	50	15.5	1.9	8.7	100	91	97	96	90	85	87	79	67	..	..
88........	F-1	5/16	1/8	45	21.0	2.6	10.7	101	100	99	95	90	86	85	79	69	..	..
89........	F-1	5/16	1/8	45	20.9	1.9	6.4	110	109	98	97	96	84	80	85	88	79	..
90........	F-1	1/4	1/8	40	14.3	1.0	2.4	116	113	97	95	92	92	84	85	90	87	75
91........	F-1	1/4	1/8	30	12.4	0.83	2.8	104	104	98	93	94	85	79	83	89	83	..
92........	P-2	9/32	....	40	16.6	0.47	9.4	101	86	96	92	84	84	78	64	51	..	..
93........	P-2	9/32	....	40	16.6	0.67	3.2	108	104	93	90	93	91	93	91	78	66	..
94........	P-2	9/32	....	29	14.5	....	2.0	103	104	95	93	94	90	88	85	87	73	..
96........	G-1	1/4	7/32	40	18.5	0.24	4.7	112	123	99	98	97	93	89	79	67	56	..
97........	G-1	1/4	7/32	30	15.8	0.25	2.2	110	115	96	98	95	94	94	93	87	71	..

TABLE 14—(*Concluded*)

Test no.	Sprinkler designation	Nozzle diameters, inches		Pressure, pounds per square inch	Discharge, gallons per minute	Rate of rotation, revolutions per minute	Wind, miles per hour	Diameter of pattern, feet		Uniformity coefficients, in per cent, for various spacings between sprinkler lines, S_2								
								North-south	East-west	20 feet	30 feet	40 feet	50 feet	60 feet	70 feet	80 feet	90 feet	100 feet
98	G-1	1/4	7/32	30	16.0	0.28	2.4	105	107	94	96	94	96	93	85	75	63	..
99	G-1	5/16	7/32	40	22.9	0.20	4.1	122	125	98	98	98	95	92	93	90	79	68
100	G-1	5/16	7/32	30	19.6	0.20	12.6	117	99	97	97	86	85	88	88	76	65	..
101	G-1	5/16	7/32	40	22.4	0.19	9.8	117	106	98	98	94	86	88	89	79	67	..
102	G-1	5/16	7/32	20	16.2	0.24	8.6	91	93	98	92	93	82	87	89	78	64	..
103	L-1	5/16	11/64	40	22.5	0.68	2.1	122	125	95	98	92	85	80	78	71	65	57
104	L-1	5/16	11/64	45	23.9	2.4	4.4	107	108	99	96	94	88	81	82	74	62	..
105	L-1	5/16	11/64	35	21.1	3.9	9.8	96	102	97	92	80	73	77	71	65	..	..
106	L-1	5/16	11/64	40	23.0	0.08	3.7	113	114	95	98	87	79	75	79	79	73	62
107	I-1	7/32	....	40	15.4	1.7	8.1	99	90	98	97	83	87	88	74	58	..	..
108	I-1	7/32	....	50	18.6	2.2	6.5	91	98	95	93	86	83	73	62	48	..	..
109	I-1	7/32	....	40	14.7	0.98	4.7	106	103	97	97	92	78	92	74	68	55	..
110	I-1	7/32	....	40	13.5	1.1	9.3	90	92	98	96	82	85	88	75	60	..	..
111	I-1	5/16	....	40	22.5	1.2	12.1	105	92	97	96	87	84	83	83	70	..	..
112	I-1	5/16	....	40	22.7	1.3	13.6	94	90	99	96	87	84	87	79	64	..	..
113	I-1	5/16	....	40	22.6	0.88	5.6	110	109	95	96	92	90	86	89	86	79	67
114	I-1	9/32	....	50	22.8	2.7	1.6	124	122	98	97	93	88	83	79	80	77	67
115	I-1	9/32	....	50	22.7	0.80	2.7	120	120	97	96	93	88	89	92	85	72	60
117	I-1	9/32	....	30	17.5	1.1	3.1	104	105	96	93	95	86	83	88	83	69	..
118	I-1	9/32	....	46	22.1	26.3	4.6	80	82	98	92	88	87	74	56	..	..	..
119	J-1	1/4	....	40	15.6	0.64	3.4	102	103	98	98	96	91	93	87	73	61	..
120	J-1	1/4	....	30	13.4	-0.57	3.2	98	99	97	96	95	90	90	86	74	61	..
121	J-1	9/32*	....	50	21.2	1.1	2.7	115	113	95	96	87	94	90	88	83	82	71
122	J-1	1/4*	....	50	18.0	0.99	5.9	109	114	97	96	94	94	90	83	70	..	..
123	J-1	1/4*	....	50	18.3	0.36	4.2	122	121	98	98	90	91	95	90	81	..	..

124.........	J-1	1/4	....	40	16.2	0.55	8.8	92	100	97	97	88	89	90	76	..	..	..
125.........	J-2	1/4	....	50	14.8	1.54	9.7	108	111	98	98	91	87	90	89	74	..	..
126.........	J-2	1/4	....	50	15.1	1.84	9.2	100	106	99	97	88	82	89	92	78	..	..
127.........	J-2	1/4	....	50	14.7	1.71	2.8	91	91	98	93	89	93	77	..	..	..	..
129.........	B-2	9/32†	5/32	50	18.9	0.38	2.5	122	122	98	96	92	87	82	85	90	85	..
130.........	B-2	9/32†	3/16	50	20.2	0.19	3.7	120	124	99	97	92	87	80	81	86	85	..
131.........	B-2	9/32†	3/16	45	19.2	41.5	2.5	69	74	92	85	76	95	77	..	..	..	..
132.........	B-4	7/32	1/8	50	12.0	0.29	2.1	122	121	98	98	87	96	95	92	86	77	..
133.........	B-4	7/32	1/8	30	9.3	0.12	3.6	96	95	99	91	93	86	89	89	87	..	..
134.........	B-4	7/32	1/8	40	10.8	0.20	3.9	110	113	98	94	95	92	93	87	74	..	..
135.........	C-1	9/32	1/8	50	19.2	0.42	2.8	130	128	99	99	98	94	85	84	89	91	84
136.........	C-1	9/32	1/8	50	19.3	0.22	2.5	129	137	99	98	97	96	87	85	90	96	89
137.........	C-1	9/32	1/8	30	14.8	0.20	6.9	104	107	97	95	89	80	83	86	79	65	52
138.........	C-1	9/32	1/8	40	16.8	0.30	8.5	112	103	98	99	89	78	89	93	80	66	53
139.........	C-1	9/32	1/8	40	16.6	0.24	7.5	120	117	99	97	98	88	82	87	96	86	73
140.........	C-1	9/32	1/8	20	12.0	0.29	3.7	100	95	97	89	95	78	73	82	90	..	..
141.........	M-1	5/16	1/8	50	20.2	2.2	4.7	116	121	99	99	97	87	81	83	83	80	69
142.........	M-1	5/16	1/8	49	21.8	0.25	1.7	140	140	99	97	97	93	96	90	88	90	89
143.........	M-1	5/16	9/64	45	21.2	0.46	2.1	128	129	98	98	92	94	96	91	89	89	84
144.........	M-1	5/16	9/64	45	21.6	2.3	2.3	123	125	99	97	96	92	81	81	88	93	84
145.........	L-1	1/4	....	50	17.0	2.1	6.3	108	101	98	95	93	85	84	81	72	67	..
146.........	L-1	1/4	....	40	15.2	7.9	3.4	117	110	98	97	95	89	87	89	81	67	..
147.........	L-1	1/4	....	30	13.3	0.28	2.6	111	111	96	95	94	87	86	87	85	72	..
148.........	L-1	1/4	....	50	17.1	0.51	3.2	117	117	97	98	95	89	87	89	86	74	..
149.........	L-1	1/4	....	50	17.0	51.0	5.6	79	79	98	91	94	84	64	..	..	..	..
162.........	G-2	3/16	1/8	30	8.5	0.29	2.0	90	96	97	91	92	93	88	77	..	..	..
163.........	G-2	3/16	1/8	40	9.6	....	4.9	112	116	98	96	93	96	92	79	66	..	..
164.........	G-2	3/16	1/8	32	8.7	....	0.5	95	98	98	95	88	78	85	96	80	..	..
165.........	G-2	3/16	1/8	40	10.0	....	3.9	112	110	99	99	90	86	93	93	78	..	..
166.........	G-2	3/16	1/8	40	9.7	0.20	1.3	108	111	98	98	97	88	89	97	86	..	..
169.........	G-3	1/4	7/32	30	16.5	....	7.2	105	106	98	97	96	93	94	87	74	61	..
170.........	G-3	1/4	7/32	40	19.3	....	2.6	121	122	99	98	98	97	96	91	80	69	..

* Main nozzle from sprinkler L-1 used for these tests.

† Angle of elevation of nozzle lowered to about 14 degrees above the horizontal; normal angle of sprinkler nozzles 25 to 30 degrees.

TABLE 15

SUMMARY OF DATA IN TABLE 14 GIVING AVERAGE UNIFORMITY COEFFICIENTS FOR SEVERAL TESTS ON THE SAME SPRINKLER UNDER SIMILAR CONDITIONS

Sprinkler	Test no.	Average wind, miles per hour	Average pressure, pounds per square inch	Average rate of rotation, revolutions per minute	Average diameter of pattern, feet	Average uniformity coefficient, in per cent, for various spacings between sprinkler lines, S_2								
						20 feet	30 feet	40 feet	50 feet	60 feet	70 feet	80 feet	90 feet	100 feet
A-1	3, 4	2.1	46	1.3	102	96	91	91	92	88	85	75	..	..
B-1	8, 9, 10, 57, 58, 59	14.0	40	...	96	98	95	88	85	84	78	67	..	..
B-1	6, 13, 55, 56	8.0	42	1.1	100	98	96	89	86	88	81	70	57	..
B-1	7, 14, 15, 16, 17, 54	3.1	38	0.5	118	99	97	95	90	85	88	90	83	73
B-2	22, 23, 24, 36, 37, 39, 67, 68	1.7	41	1.8	111	98	95	93	89	81	82	87	86	78
B-2	12, 19, 20, 38	4.5	40	3.4	102	98	94	92	83	84	89	83	70	..
B-4	132, 133, 134	3.2	40	0.2	109	98	94	93	91	92	89	79	..	..
C-1	26, 28, 135, 136	2.0	41	1.6	122	97	98	95	95	87	87	90	90	81
C-1	27, 137, 138, 139	6.7	40	1.0	109	98	97	93	86	86	90	85	72	..
F-1	85, 86, 89, 90, 91	3.8	35	1.2	105	97	93	93	87	82	84	85	76	..
F-1	83, 84, 87, 88	9.3	38	1.4	94	97	93	89	84	87	83	71	..	..
G-1	97, 98, 99, 170	3.4	35	0.2	116	97	97	96	96	94	91	83	70	..
G-1	96, 100, 101, 169	8.6	35	0.2	109	98	97	94	89	90	86	74	62	..
G-2	163, 164, 166	2.2	37	...	107	98	96	93	87	89	90	77	..	..
I-1	109, 113, 114, 115, 117	3.5	42	1.3	112	97	96	93	88	87	86	81	70	..
I-1	107, 108, 110, 111, 112	9.9	42	1.5	98	98	96	85	85	84	74	60	..	..
J-1	119, 120	3.3	35	0.6	100	97	97	96	91	92	86	74	61	..
J-1*	121, 122, 123	4.3	50	0.8	116	97	97	90	93	92	87	78	..	..
J-2	125, 126	9.4	50	1.7	107	98	97	89	85	90	91	76	..	..
L-1	103, 104, 106, 145, 146, 147, 148	3.7	42	2.0	113	97	96	93	86	84	83	78	69	..
M-1	141, 142, 143, 144	2.7	47	1.0	128	99	98	95	92	89	85	87	88	81
P-2	93, 94	2.6	34	...	105	94	92	93	90	91	90	82	70	..
B-2†	129, 130	3.1	50	0.3	120	98	97	92	87	81	83	88	85	..

*Main nozzle from sprinkler L-1.
† Nozzle angle, 14°.

TABLE 16

UNIFORMITY COEFFICIENTS FOR ACTUAL SPRINKLER PATTERNS

Spacing along line, S_1, feet	Uniformity coefficients, in per cent, for various spacings between lines, S_2						
	40 feet	50 feet	60 feet	70 feet	80 feet	90 feet	100 feet
Pattern for test no. 11 (fig. 34)							
10	90	77	69	76	89	81	..
20	79	77	65	65	72	66	..
30	86	73	68	72	78	70	..
40	76	56	45	50	57	52	..
60	..	57	53	46	49	42	..
60 T*	..	56	47	41	51	42	..
Pattern for test no. 16 (fig. 29)							
10	96	95	89	88	93	92	82
20	95	95	89	88	93	92	81
30	93	94	89	88	91	90	81
40	94	92	88	88	91	89	81
60	..	84	82	83	83	82	74
60 T	..	90	84	81	82	79	74
80	..	..	84	80	78	75	70
80 T	..	..	75	76	76	76	73
Pattern for test no. 88 (fig. 39)							
10	93	93	95	83	68	..	..
20	91	92	94	83	68	..	..
30	90	90	92	83	69	..	..
40	85	85	84	79	66	..	..
60	..	75	71	71	60	..	..
60 T	..	72	77	71	60	..	..
Pattern for test no. 118 (fig. 43)							
10	96	87	68	50	..	..	..
20	93	87	68	50	..	..	..
30	85	81	66	49	..	..	..
40	84	78	63	48	..	..	..
60	72	72	62	44	..	..	..
60 T	82	79	61	44	..	..	..
Pattern for test no. 132 (fig. 31)							
10	90	97	94	90	86	80	..
20	90	96	94	90	86	80	..
30	89	95	92	90	86	79	..
40	89	91	90	88	85	79	..
60	..	89	88	87	83	76	..
60 T	..	91	89	86	83	77	..
80	..	..	82	83	78	74	..
80 T	..	..	86	85	82	75	..
Pattern for test no. 170 (fig. 33)							
10	98	96	95	91	81	69	59
20	97	96	95	91	80	69	59
30	97	96	94	91	80	69	59
40	96	95	94	90	80	69	58
60	..	94	93	89	80	69	58
60 T	..	93	92	89	80	69	60
80	..	..	79	79	75	66	57
80 T	..	..	89	86	77	66	57

* T denotes a triangular arrangement of sprinklers; others are rectangular.

covered is reduced when operating conditions are unfavorable. For both of these tests, the size of the sprinkler nozzles and other factors were comparable with tests 16 and 170. (For specific data on these tests see table 14).

EVAPORATION LOSSES

A question frequently asked concerning sprinkling is, How much water is lost by evaporation when water is sprayed into the air? Generally it has been assumed that the loss directly from the spray may be appreciable, especially on warm, dry days, and when the wind is blowing. In addition to the loss from the spray there are direct evaporation losses from wet surfaces during and following every application of water.

EVAPORATION FROM THE SPRAY

There has been little published from which one might obtain information on the evaporation from water drops moving rapidly through the air. To compare sprinkling with other methods of irrigation, one must separate these losses from those which occur subsequently from the wet soil, and which are common to all irrigation methods. In order to obtain some information on this subject, the sprinkler tests for distribution of water were planned so that the total amount of water applied to the entire area could be calculated from the amounts caught in the cans. This was one of the principal reasons for spacing the cans uniformly over the entire area.

Direct Measurement of Evaporation Losses.—Before evaporation losses could be ascertained it was first necessary to know how accurately the total amount of water falling on the area could be determined by this method. To do this, a series of tests were made in the early morning before sunrise when the relative humidity is highest and the air temperature lowest. It was reasoned that the evaporation at this time of day would be very low, possibly negligible. The calculated loss, or difference in the amount of water falling on the area, and that discharged from the sprinklers, should then be low. For fifteen early-morning tests, where the relative humidity exceeded 75 per cent, the calculated loss was 3.9 ± 0.35 per cent. This loss included that represented by the water which would cling to the inside of the cans when emptied. By carefully weighing cans dry and after pouring water from them, this part of the loss was found to average about 1 cubic centimeter, or about 3 per cent of the average amount caught. Judging from these early-morning tests, the total amount of water falling on the area can be determined with reasonable accuracy from the amounts caught in cans uniformly spaced over the area.

The calculated losses for afternoon tests varied from less than 10 per cent to a maximum of 42 per cent for one test when the air temperature averaged 105°F and the relative humidity about 15 per cent. These losses did not show a very high correlation with the evaporation from atmometers, or with such factors as relative humidity and vapor pressure deficit, but sunshine appeared to have an important effect. Further study showed definitely that a large part of the calculated loss could be accounted for by evaporation from the cans. To reduce this loss, funnels were soldered into the cans. Comparative tests were made by placing 50

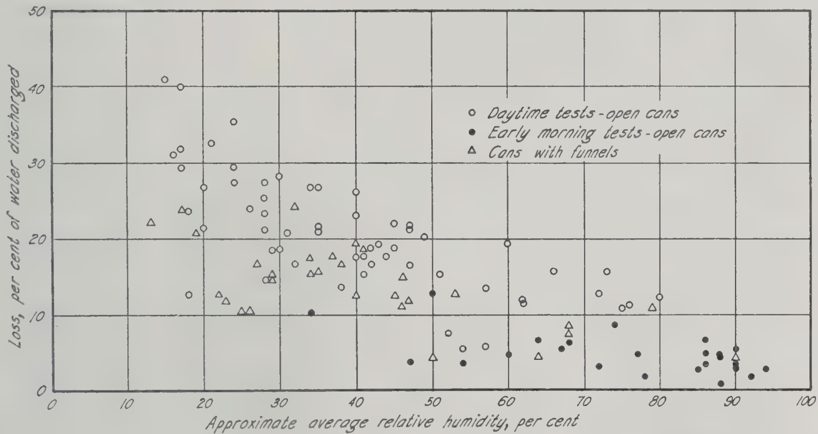

Fig. 56.—Evaporation loss calculated from sprinkler tests. This loss includes that from the spray, that from the cans during the test and period of measurement, and that represented by the amount of water clinging to the cans when they are emptied.

cubic centimeters of water in each of five cans with, and five cans without, funnels. After 3 hours the average loss from the cans with funnels was only 0.75 cubic centimeter per hour, or about 10 per cent of that from the open cans.

The first 122 sprinkler tests were made with open cans spaced 10 feet apart in each direction. For subsequent tests, the cans with funnels were spaced 7.07 feet apart in diagonal rows, providing one can to each 50 square feet (fig. 27).

The use of the cans with funnels did not, however, materially change the calculated losses as indicated by figure 56, which shows the loss plotted against the approximate average relative humidity. The reason, probably, is the evaporation of water from the wet surface of the funnel. No way was found to eliminate this error. The measured losses should, therefore, be considered not as evaporation losses from the spray alone, but as the combined losses from the spray and from the cans during the

test and the period of measurement following the test, which averaged about 30 minutes.

Indirect Method of Estimating Evaporation Loss from the Spray.—The evaporation loss from the spray may be determined approximately from thermodynamic principles. Evaporation of water requires heat. The number of calories necessary to evaporate one gram of water, called the latent heat of evaporation, varies from 539.6 for water at 100° C (boiling point) to 595.9 for water at 0° C (freezing point). It is about 585 for water at 68° F. Three sources of heat are available for evaporating water from a spray: (1) heat from the water, (2) heat absorbed from the air, and (3) radiant heat, principally from the sun. If all of the heat came from the water, it would require a temperature drop of about 10.5° F to evaporate 1 per cent of the water.

When the water is cooler than the air, as normally in the daytime, the water will absorb heat from the air, and the drop in temperature will be less than 10.5° F for 1 per cent loss. Absorption of radiant heat will also increase the evaporation for the same temperature change. When the initial water temperature is the same as the wet-bulb temperature of the air, an equilibrium condition exists; all the heat required for evaporation comes from the air, and the water remains at a constant temperature. When the initial temperature of the water is lower than the wet-bulb temperature, it will increase even though some evaporation still takes place. The evaporation would be zero, however, if the water temperature was at the dew point; and if it were lower than this, condensation would occur, and there would be a gain rather than a loss of water.

Neglecting the radiant heat and considering only that from the air and water, an equation has been derived from which the evaporation loss can be determined for any given change in the temperature of the water, provided the air temperature and humidity are known. This approximate expression for the evaporation loss from the spray is

$$E = \frac{100C\,\Delta t}{r}\left[\frac{P_w - P_a}{P_w - P_a - 0.00037\,B(t_a - t_w)}\right] \qquad (26)$$

where E is the loss of water from the spray expressed as a percentage of the amount discharged; C is the specific heat of water, calories per gram per degree Fahrenheit; r is the heat of vaporization, calories per gram; Δt is the drop in temperature of the water from the time it leaves the nozzle until it reaches the ground; t_w is the mean water temperature, degrees F; t_a is the air temperature, degrees F; P_w is the vapor pressure of water at temperature t_w, inches of mercury; P_a is the pressure of the water vapor in the air, inches of mercury; and B is the barometric pres-

sure, inches of mercury. Evaluating the constants, letting $C = 0.555$, $r = 585$, and $B = 30$, the expression becomes

$$E = 0.095\,\Delta t\left[\frac{P_w - P_a}{P_w - P_a - 0.011\,(t_a - t_w)}\right]. \qquad (27)$$

The expression within the brackets varies from less than 1.0, when the temperature of the water exceeds the air temperature, to infinity when the water temperature is the same as the wet-bulb temperature; and from minus infinity to zero as the water temperature decreases to the dew point.

Equation 27 fails to take into consideration the very small drops of water which are completely evaporated or blown away by the wind, and which do not contribute to the final temperature of the water as it reaches the ground. A study of the distribution of size of drops, however, indicates that only a very small part of the water discharged is in the form of tiny drops that are lost, and it is believed that this would not cause an appreciable error in the determination of the evaporation loss from the spray.

Several tests have been made to determine the temperature drop of the water between the sprinkler and the ground. The water was caught in a thermos bottle with a large funnel. To obtain a large quantity of water quickly and to avoid errors caused by changes in the temperature of the water after it is caught, the rotating sprinklers are stopped during the catch. For some of these tests, in order to increase the evaporation loss and to more nearly approach field conditions, the water was warmed several degrees above the normal temperature of the well water which was about 65° F. This was accomplished by installing two electric heaters in the pipe line supplying water to the sprinkler. The temperatures were read with a thermometer graduated to 0.2° F. Five tests on rotating sprinklers with initial water temperatures of 69.5° to 84°, and with air temperatures ranging from 75° to 101°, showed decreases in water temperature from 1° to 7° corresponding to evaporation losses of 0.23 to 0.81 per cent. Another test on a small spray nozzle, with an initial water temperature of 98.7° and an air temperature of 100.5°, resulted in a temperature drop of 20.7°, corresponding to a loss of about 2 per cent.

From these measurements of the temperature change of the water as it passes through the air, one must conclude that the evaporation loss from the spray is negligible in comparison with subsequent losses from the wet soil and vegetation. Even when one considers the possible effect of solar radiation, and the increase in vapor pressure of the water when in the form of small drops, one cannot account for evaporation losses from the spray of more than 2 per cent of the amount applied.

EVAPORATION LOSSES FROM WET SURFACES

Evaporation from soils and other wet surfaces, during and following an application of water, may be appreciable. This loss is relatively more important in connection with irrigation by sprinkling than with irrigation by other methods because (1) lighter applications are generally made by sprinkling than by surface irrigation, so that a larger percentage of the water applied may be lost by subsequent evaporation; and (2) the cost of applying water by sprinkling is generally higher, so that the evaporation loss represents a greater economic loss.

Evaporation Losses from Moist Soils.—The evaporation loss from moist soils has long been a subject of discussion and experiment by those interested in irrigation. Fortier and Beckett[20] conducted experiments to determine the loss from undisturbed and cultivated soils at Davis after an irrigation. Veihmeyer[21] made similar studies at Mountain View. Briefly, these experiments indicate that 1 to 2 inches of water evaporates from the soil within 3 to 4 weeks after an irrigation, more than half of which occurs during the first five days. This loss is not prevented by cultivation, partly because most of it occurs before the soil is dry enough to work. Practically all of the evaporation loss is from the first foot of soil, and most of it from the first 4 inches. The rate of loss by evaporation after the first week is negligible in comparison with the rate of extraction of water by plants.

The actual loss by direct evaporation from a cropped soil is probably considerably less than from a bare soil because the ground is shaded, partially at least, by the crop, and also because the growing crop rapidly reduces the moisture content of the soil by transpiration, which lessens the opportunity for evaporation to occur.

According to other experiments, the rate of evaporation from saturated soils is about the same as from a free water surface, or about 0.3 inch per day in the Sacramento Valley during the summer. With a water table 6 inches below the surface, the evaporation loss averaged about 0.21 inch per day during the summer; but this decreased to about 0.06 inch per day with the water table 2 feet below the surface.

When relatively small amounts of water are applied to exposed soils at frequent intervals by sprinkling, a common practice in the spring, much of the water may be lost by evaporation. In some instances applications of about 1 inch are made at weekly intervals to aid the germination and starting of a crop and to prevent the drying out and crusting

[20] Fortier, Samuel, and S. H. Beckett. Evaporation from irrigated soils. U. S. Dept. Agr. Office of Experiment Stations Bul. 248:1–77. 1912.

[21] Veihmeyer, F. J. Some factors affecting irrigation of deciduous orchards. Hilgardia 2(6):125–291. 1927.

of the surface soil at this time. Most of this water may be lost directly from the soil by evaporation. When, on the other hand, a growing crop completely covers and shades the soil, and when the applications are sufficient to give a penetration of 3 to 6 feet, only a relatively small percentage of that applied may be lost by direct evaporation.

Rate of Evaporation from Free Water Surfaces.—The evaporation from free water surfaces is measured at a number of Weather Bureau stations, and at many other places in California and elsewhere. The evaporation as measured at these stations has been found to depend largely upon the type of evaporation pan used, and upon its exposure. For this reason various organizations, such as the Weather Bureau, have standardized their evaporation equipment to facilitate comparisons. Tests have also been made to determine the coefficients by which the evaporation from various types of pans must be multiplied to obtain the equivalent evaporation from a lake surface. For the standard Class A Weather Bureau pan the coefficient most generally used is 0.70.[22] A Class A Weather Bureau evaporation station has been maintained at Davis since 1926. Besides the regular equipment, a recording evaporimeter is used so that instantaneous rates of evaporation can be obtained. The average daily evaporation at Davis for a fourteen-year period was as follows: May, 0.27 inch; June, 0.31; July, 0.35; August, 0.32; and September, 0.24. According to evaporimeter records, the maximum hourly rate sometimes exceeds 0.05 inch and averages about 0.04 during the afternoon.

Since water is sometimes applied with sprinklers at rates as low as 0.10 inch per hour, an appreciable evaporation loss may occur during and immediately after an application. Even with application rates of 0.25 to 0.50 inch per hour, more than 10 per cent of the water may evaporate as it is applied during the afternoon. The evaporation loss at night, however, is usually very low.

Interception and Subsequent Evaporation of Water from Plants.—When crops are sprinkled, part of the water is intercepted by the foliage and later evaporated without reaching the soil. Studies of rainfall interception by various investigators indicate that an appreciable amount may be caught by trees and other plants, especially when the rain occurs in small storms. The determination of rainfall reaching the soil under a vegetative cover is difficult, and results obtained are not always consistent. Furthermore, the interception is generally reported in per cent of rainfall, and therefore depends upon the intensity and duration of

[22] American Society of Civil Engineers. Evaporation from water surfaces, a symposium. Amer. Soc. Civ. Engin. Trans. 99:671–747. 1934.

the storm. Clark[23] made determinations of the maximum interception capacity of many plants. From his data it appears that few crops can retain 0.1 inch of water, although his attempts to measure interception by catching water in pans under the vegetation indicate much larger losses.

Interception of rainfall and that for water applied with sprinklers should differ principally in the amount that evaporates during the application. The evaporation rate while sprinkling may be high, whereas during a rain evaporation rates are generally very low. The presence of water on the foliage should temporarily reduce the rate of evaporation from the soil and the rate of transpiration from the leaves.

DESIGN AND OPERATION OF SPRINKLER SYSTEMS

Methods of Operation.—With respect to the method of operation, portable sprinkler systems may be divided into two general classes: first, those in which the rate of application is fairly high and the sprinkler lines are moved frequently; second, those in which the rate is relatively low and the moves are rather infrequent. Most systems with portable pumping plants fall into the first class. The capacity of the system is generally limited by the power available for operating the pump, while the length of portable pipe that can be effectively used is governed by the dimensions of the field and the general layout of the system. The sprinklers selected are of a capacity that will effectively utilize the pumping plant. The rate at which the water is applied receives little consideration; often it is too high, and water accumulates on the ground surface before adequate penetration is obtained. The result, usually, is that light frequent applications are made where heavier and less frequent applications would give better results and be more economical. Frequent moves mean continuous employment of labor together with a relatively low operating efficiency because of the larger proportion of time lost. This is especially true with the single-line arrangement. Most of these systems operate continuously day and night, the lines being moved every 2 to 6 hours. Moving pipe at night is objectionable because it takes a crew considerably longer to make moves at night than during the day, and because working conditions at night are disagreeable.

Under the second method of operation, the water is applied at such a rate that the moves can be made at convenient times each day. The ideal arrangement is to move the lines twice a day—morning and evening so that both moves are made in daylight. From 3 to 8 inches of water is generally required to wet dry soils to the depth from which moisture is

[23] Clark, O. R. Interception of rainfall by prairie grasses, weeds, and certain crop plants. Ecological Monographs 10:243–77. Apr., 1940.

extracted by most crops. Applications of these amounts must be made fairly slowly so that the soil can absorb the water without runoff. Under some conditions it is necessary to extend the period of application to 24 hours to avoid runoff.

When sprinkler systems are operated on this basis, continuous attention may not be required. The operating cost will then be lower, since 60 to 80 per cent of the actual expense of operating portable systems is for labor. If this help can be employed only during the time required for moving pipe, or used effectively elsewhere during the time when they are not needed, the saving will be appreciable. There are many possible schemes for operating a system in this manner.

When a portable pumping plant is used, continuous attention may be necessary to prevent damage if the pump loses its prime or if any other emergencies arise. When moves are made only twice daily, it may be practicable to employ one man for the day shift and one man for the night shift, having the shifts overlap at the time of moving. In this case, each shift would be 12 hours plus the time required to move the system. Long shifts are feasible because during most of the time no work is required and the operator can rest.

Where adequate applications can be made in about 8 hours, three moves a day may be desirable. With one move at dawn, another at noon, and a third just before dark, three fairly equal periods of operation can be obtained during the summer months. Two men working alternate shifts overlapping the moving period could handle a system on this schedule with less physical effort than under the conditions now common. Three men working overlapping shifts of about 9 hours may, however, be more desirable for such a schedule.

For small sprinkling systems operated by the owner, a 12-hour set is especially advantageous; it permits the farmer to carry on his irrigation work continuously, and yet take care of other farm operations. This method of operation requires a system that is free from troubles; sprinklers sometimes clog or stop rotating, or the pump may lose its prime. Usually it is more feasible when pressure supply lines and stationary electric-driven pumping plants are used. At present this method is being practiced to a much greater extent with orchard systems than with other types.

Capacity of Sprinkler Systems.—In planning any sprinkler system one must first consider those factors that influence the selection of the size of the system. In general, the lowest initial cost results when a system is planned for continuous operation with a capacity that will just satisfy crop requirements. This may or may not be the most economical system to operate. Sprinkler systems can be designed to use effectively a smaller

flow than is desirable for any other method of operation—a feature advantageous to the operator of a small farm or orchard, since he need not invest in an irrigation system with a capacity several times larger than necessary for his acreage.

Whether or not a small sprinkler system, operated more or less continuously, will be more economical than a larger system, operated only a few days for each irrigation, depends primarily upon the method of operation. If it requires continuous attention, a small system may not be economical because the labor cost of operating it may be very high—all out of proportion to the cost of the water or the cost of power for pumping. Where continuous attention is not necessary, and especially where the attention required can be given at convenient times, a small system operating continuously will also be the most economical to operate. Such systems are especially desirable for orchards and pastures. For large field-crop portable systems with portable pumping plants, one may find it difficult to arrange the layout for slow rates of application that will permit 12-hour or even 8-hour periods of operation.

Sprinkler systems designed for continuous operation must have sufficient capacity to meet the peak requirements during the critical part of the year. For orchards and perennial crops the maximum water requirement occurs during June, July, and August. For some annual crops it may occur earlier or later in the season. Crop transpiration depends largely upon the climate—sunshine, temperature, and humidity. For interior valley conditions, crops that completely cover the ground—alfalfa, sugar beets, and the like—will transpire water at a maximum rate of about 6 to 8 inches per month during the period June to August. Mature deciduous trees transpire about the same amount. Citrus requirements are a little lower. For some coastal areas, applications of 2 to 4 inches per month are adequate.

One acre-inch of water in 30 days is equivalent to 0.628 gallon per minute continuous flow. To supply 8 inches in a month, therefore, requires a continuous flow of about 5 gallons per minute per acre. For valley conditions, this is approximately the minimum flow that will completely satisfy crop requirements. For systems designed to be operated only during the day, a flow of about 10 gallons per minute per acre will be required. Where additional time must be allowed for cultural operations, systems with still greater capacity must be provided. Where conditions are such that it is economical to provide a complete irrigation in a short period, a still larger flow may be desirable. A convenient relation to remember is that the required flow

$$Q = \frac{450\,dA}{T} \tag{28}$$

where Q is the flow in gallons per minute; d is the average depth of water applied in inches; A is the area in acres, and T is the time in hours. For example, to apply a 4-inch application on a 10-acre tract in 48 hours requires

$$Q = \frac{450 \times 4 \times 10}{48} = 375 \text{ gallons per minute.}$$

Rate of Application.—Besides the capacity of the system, one must consider the rate of application. This may be governed by the soil condition (the rate at which the soil will absorb the water) or by the method of operation (the period of time in which one wishes to apply a given amount of water).

Coarse-textured soils (sandy and gravelly soils) generally absorb water rapidly, usually at any normal rate at which it might be applied with a sprinkler system. Fine-textured soils (fine silts and clays) absorb water more slowly. The rate of absorption decreases with time. Some clay adobe-type soils absorb water very rapidly when dry because of the granular structure and large number of cracks that form when the soil dries. For example, when dry, such a soil might absorb the water at a rate of several inches per hour for a few minutes; but the rate of absorption might decrease rapidly, perhaps becoming a small fraction of an inch per hour after several hours of application.

The maximum rate at which the water should be applied will depend upon the amount of each application. When only 1 or 2 inches of water is desired, high rates of application may be used; but if 4 to 6 inches or more is to be applied, much slower rates are required. A knowledge of rainfall rates and of the ability of soil to absorb prolonged rains may be used as a basis for selecting suitable rates for sprinkler application.

The rate at which soils absorb water also depends somewhat upon how the water is applied. Large drops resulting from low pressures tend to puddle and seal the surface of the soil much sooner than a fine atomized spray. The condition of the soil surface is also important. A cultivated soil left somewhat cloddy will absorb the water more rapidly than one that has been pulverized to a fine dust. A hard compacted or crusted soil will generally absorb water slowly. The presence of organic matter on the surface appreciably increases the rate of absorption for some soils. Rates of application varying from about 0.1 to more than 1 inch per hour are practicable with sprinkler systems.

Depth of Application.—Soils act as a reservoir for water, retaining in it the pore spaces between the soil particles until it is used by plants or lost by evaporation. When a soil is irrigated, the water penetrates rather rapidly until the moisture content is reduced by drainage to a

certain percentage, called the field capacity, after which further movement and penetration into dry soil becomes very slow. For practical purposes, the field capacity may be considered as the amount of moisture a soil will retain against the downward force of gravity, or the upper limit of the available-moisture range. It varies greatly with soil texture, and to lesser extent with other factors. In general, fine-textured soils have a higher field capacity than coarse-textured soils; clay loams and clays range from about 20 to 30 per cent, whereas fine sands and sandy loams vary from about 8 to 15 per cent. In terms of quantity, the amount of water held by a soil at field capacity varies from about 1 inch per foot depth of soil for sandy loam to 4 inches for some clays.

Not all the water held by a soil is available for plant use. The lower limit of the readily available moisture range is called the permanent wilting percentage. At this moisture percentage plants wilt and do not revive until water is added to the soil. Generally plants do not die when they wilt, but their growth practically ceases; in some instances, they shed their leaves. The permanent wilting percentage is the same for all kinds of plants grown in the same soil, although it varies widely with different soils. Sometimes, however, shallow-rooted plants wilt before other deeper-rooted plants growing side by side. Plants differ in their ability to withstand long periods in dry soils; some die, others go into a dormant state.

The permanent wilting percentage is influenced primarily by soil texture; for many soils, it is approximately half that of the field capacity. This rule, however, cannot be applied generally because some soils show wide departures from it. A typical Aiken clay loam, for example, with a field capacity of about 30 per cent has a wilting percentage of 21 per cent. In contrast, a typical Fresno fine sandy loam has a field capacity of about 10 per cent and a permanent wilting percentage of about 3. The Aiken clay loam holds three times as much water as the Fresno fine sandy loam; but that available to plants is nearly the same.

In addition to the ability of the soil to hold water, the depth of application is influenced by the rooting depth of the crop grown. This varies with different crops, and also depends upon the soil and upon the presence of hardpan or a water table near the surface. For many field crops growing in deep uniform soils, roots are active to much greater depths than is commonly supposed. Judging from recent investigation at Davis[24], sugar beets extract moisture from a depth of 6 feet; tomatoes from about 7 feet. Sugar beets showed little evidence of need for water until the first 4 feet of soil was dried to the permanent wilting percentage. In contrast, potatoes growing in an Aiken loam indicated a need for

[24] Doneen, L. D. Studies in the irrigation of sugar beets. Pacific Rural Press 131 (8):307. 1941.

water when the first foot of soil was dry, though there was still available water in the second foot.[25] This difference is attributed partly to the soil, as other crops growing in this soil require frequent irrigations. Studies at Shafter[26] showed that cotton extracts moisture from a depth of 6 feet.

Alfalfa roots extend well below 6 feet.[27, 28] Generally, deciduous trees are deep-rooted. Prunes[29] extract moisture from below 9 feet, and walnut roots[30] are active to a depth of 12 feet. Although the roots of citrus[31] extend below 4 feet, most of the extraction is from the first 2 feet.

In general, it is considered good irrigation practice to wet the soil to the depth of the rooting zone (that depth from which water is extracted by plants) each time it is irrigated. Sprinkling is practiced on many shallow soils underlaid with rock, hardpan, gravel, or a high water table. Care must then be exercised; if too much water is applied, the soil may become waterlogged, or an appreciable amount may be lost by deep percolation.

Sometimes a shallow sandy loam surface soil is underlaid with a very heavy subsoil. Because of the increased root activity in the surface soil, and also because of its lower water-yielding capacity, the moisture is extracted from the surface soil sooner than from the subsoil, and rather frequent irrigations are required to maintain available moisture in it. When excessive applications are made, the excess water drains into the already wet subsoil, and may actually keep it in a more or less saturated condition. Roots tend to die out in the wet subsoil and become concentrated near the surface. Sprinkling has been found especially beneficial in overcoming this condition in citrus orchards. Light, frequent applications maintain available moisture in the surface soil without contributing water to the subsoil. Over a period of time this permits roots to develop to a greater depth. Greatly improved tree conditions have been noted in some instances.

Under different soil and crop conditions, applications varying from 1 to 6 inches or more might be desirable. Sprinkling is most extensively

[25] Edlefsen, N. E. Effect of soil moisture characteristics on irrigation requirements. Agr. Engin. 18:247–50. 1937.

[26] Beckett, S. H., and Carroll F. Dunshee. Water requirements of cotton on sandy loam soils in southern San Joaquin Valley. California Agr. Exp. Sta. Bul. 537:1–48. 1932. (Out of print.)

[27] Beckett, S. H., and M. R. Huberty. Irrigation investigations with field crops at Davis, and at Delhi, California 1909–1925. California Agr. Exp. Sta. Bul. 450:1–24. 1928. (Out of print.)

[28] Unpublished data, experiments in progress.

[29] Hendrickson, A. H., and F. J. Veihmeyer. Irrigation experiments with prunes. California Agr. Exp. Sta. Bul. 573:1–44. 1934.

[30] Veihmeyer, F. J., and A. H. Hendrickson. Soil moisture as an indication of root distribution in deciduous orchards. Plant Physiol. 13(1):169–77. 1938.

[31] Beckett, S. H., Harry F. Blaney, and Colin A. Taylor. Irrigation water requirement studies of citrus and avocado trees in San Diego County, California, 1926 and 1927. California Agr. Exp. Sta. Bul. 489:1–51. 1930.

practiced under conditions requiring light frequent applications, where it has a relatively greater advantage over other irrigation methods. Applications of 2 to 4 inches are most common, and satisfy requirements in many places.

To summarize: a sprinkler system should be planned with adequate capacity for crop requirements, and it should be capable of applying proper amounts at such rates that the soil can absorb the water without runoff.

Sprinkler Capacity.—Having decided upon the general method of operation, the required capacity of the system, and the suitable rates of application, one comes to the more technical phases of the design problem. The general layout of the system and the spacing of sprinklers must be considered. To determine the proper spacing for best distribution of water one must understand sprinkler performance. The capacity of the sprinklers may be governed by the dimensions of the field and the total capacity of the system, or by the rate at which the water can be applied. For large portable systems, with portable pumping plants, the capacity of the system is usually limited by the power available for pumping, and the capacity of the sprinklers by the number that can effectively be used, which depends upon spacing and field dimensions. Sometimes the capacity of a system is governed by the sprinkler discharge required to make a given application in a certain time interval, and by the number of sprinklers for most effective arrangement.

The required sprinkler discharge, to apply a given quantity of water in a certain period, can be conveniently calculated from the following expression:

$$q = \frac{d\,S_1\,S_2}{96T} \tag{29}$$

where q is the discharge of each sprinkler in gallons per minute; d is the average depth of application, inches; S_1 is the sprinkler spacings along the line; S_2 is the spacing between sprinkler lines; and T is the period of operation in hours.

Consider, for example, a typical case—an 80-acre field to be irrigated by a portable system supplied by a portable pump from a field ditch running lengthwise through the middle of the field. From the standpoint of crop requirements and method of operation a total capacity of 5 gallons per minute per acre or 400 gallons per minute will suffice. The net field dimensions are 1,290 by 2,610 feet. Six hundred feet of pipe will reach from the pump near enough to the edges of the field for the last sprinkler to cover. Fifteen sprinklers 40 feet apart, twenty sprinklers 30 feet apart, or thirty sprinklers 20 feet apart might be used on a 600-foot line; or twice as many on 1,200 feet of pipe.

Suppose a 12-hour operating schedule is preferred, and a 4-inch application is considered adequate. Because of wind conditions, the lines can be moved a maximum of 60 feet. To make the number of sets come out even, the lines should actually be moved only 59 feet. To apply 4 inches of water in about 11 hours, allowing for moves, with $S_1=40$, and $S_2=59$ would require a sprinkler discharge of

$$q = \frac{4 \times 40 \times 59}{96 \times 11} = 9 \text{ gallons per minute.}$$

With a 40-foot spacing on the line, an effective arrangement necessitates either fifteen sprinklers on a single line, or thirty on a split line. With thirty sprinklers, the total capacity would be only 270 gallons per minute, which is not adequate. A minimum capacity of $\frac{400}{30}=13.3$ gallons per minute is considered necessary. With three moves per 24 hours, allowing 7 hours' net operating time between moves, the sprinkler capacity would be

$$q = \frac{4 \times 40 \times 59}{96 \times 7} = 14 \text{ gallons per minute.}$$

Thirty sprinklers would have a total capacity of 420 gallons per minute. With three moves, or 177 feet of land covered per day, a total of $\frac{2590}{177}=14.6$ days, or 44 settings would be required to cover the field. This would allow for two 4-inch irrigations per month.

Size of Pipe.—The size of pipe required in a sprinkler system depends upon several factors. In general, the size should be such that the friction loss is reasonable. A high friction loss in the pipe lines makes it difficult or impossible to distribute the water uniformly over the area. Where water is supplied under pressure, pipe sizes must be ample to carry the required flow and leave a sufficient pressure for satisfactory sprinkler performance. Where pumping is required, the problem is fundamentally one of determining what sizes result in the lowest annual cost. Small pipe is less in first cost but it increases the pumping head and cost of pumping. There are two methods of approaching this problem. One is to set down, in the form of an integral equation, all items entering into the cost and differentiate to determine what pipe size gives minimum cost.[32] The other is to estimate the total annual cost for different pipe sizes that appear practicable, and in that way to determine the most economical size. Both necessitate assumptions regarding cost and life of pipe, that are at best only approximations.

[32] This method of attack is discussed in: Gladding, R. D. Special design problems in distribution systems for sprinkler irrigation. A paper presented at the Pacific Coast Section Meeting, American Society of Agricultural Engineers, Corvallis, Oregon, February 16, 1940. 22 p. (Mimeo.)

Friction losses in pipe of different kinds are discussed in detail in the section "Hydraulics of Sprinkler Systems." When using friction-loss tables or diagrams for the purpose of selecting pipe sizes, one may well use conservative friction factors, or coefficients, or add a certain amount—about 10 per cent—to the required flow as a factor of safety. The same principles apply to the design of stationary systems. The uniformity of distribution is then especially important. Careful consideration must be given to the arrangement and spacing of sprinklers, and to the type of sprinkler pattern. Minimum cost will result with low rates of application which permit smallest pipe sizes. Although labor costs are lower, stationary systems should also be designed for convenient operation.

Many other problems enter into the design of sprinkler systems. Some of these have been discussed in connection with the descriptions of the various systems. Although the design of a sprinkler system is essentially an engineering problem, it is also one that requires a knowledge of agriculture.

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